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Final Report

THE I-70 GREENFIELD REST AREA WETLAND PROJECTS

Shih-Chieh Kao
Ting Pong Chan
Rebeka Sultanta
Thomas Konopka
Thomas Cooper
Barry Partridge
Rao S. Govindaraju

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by

Shih-Chieh Kao
Ting Pong Chang
Rebeka Sultana
Thomas Konopka
Graduate Research Assistants

and

Rao S. Govindaraju
Professor

School of Civil Engineering
Purdue University

and

Barry Partridge
Director, Office of Research and Development
Indiana Department of Transportation

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16. Abstract

On-site treatment of wastewater at highway rest areas poses some unique and difficult challenges because of the rural locale, high variability in wastewater flow rate and strength, and lack of knowledgeable personnel on-site. As a potential alternative, a constructed subsurface wetland system was built at the I-70 rest stop nearby Greenfield, Indiana, in 2003. This wetland system, mainly composed of three wetland cells, also includes draw-and-fill and recirculation mechanisms to increase oxygen transfer to the wastewater and improve the overall treatment performance. Special considerations for highway rest areas have been emphasized. A dynamic hydraulic model was developed to help characterize the flows in the system and estimate the hydraulic retention time. The size of the Greenfield wetland was found to be sufficient in providing pretreatment that could help avoid potential surcharge from the local treatment plant, but was inadequate for direct onsite discharge. Though the draw-and-fill and recirculation mechanisms provided some treatment benefits, they raised the construction costs and maintenance needs. Constructed wetlands have been described as low-maintenance systems compared to other conventional wastewater treatment approaches, but proper maintenance of the wetland facilities was found to be a key factor in achieving good performance. Since wetland systems in highway rest areas have not been studied, this study provided useful information for possible future implementation of such systems.

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Fike Abasi	INDOT Design Division
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Merril Dougherty	INDOT Design Division
Tom Duncan	INDOT Pre-Engineering and Environment Division
Clyde Mason	INDOT Greenfield District
Steve McAvoy	INDOT Operations Support Division
Joyce Newland	FHWA Indiana Division
Barry Partridge	INDOT Office of Research and Development
Steve Sperry	INDOT Environment, Planning, and Engineering Division
Jerry Unterreiner	INDOT Pre-Engineering and Environment Division
Tom Vanderpool	INDOT Greenfield District
JoAnn Wooldridge	INDOT Greenfield District

Outside Members

Andrew Bender	J. F. New
T. Blahnik	J. F. New
Ed. Miller	Indiana Department of Health
Matt Moore	RQAW
Brian Morgan	Heritage Industries
Steve Land	INDOT/PS
David Latka	J. F. New

Purdue Team

Students	T. P. Chan, S.-C. Kao, S. Khanal, T. Konopka, N. Shah, S. Sharma, R. Sultana, S. Tripathi
Laboratory and Field Research Coordinator	T. J. Cooper
Faculty	J. E. Alleman, R. S. Govindaraju, R. Wukasch

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While this study has been funded by Joint Transportation Research Program (JTRP) at Purdue University, this report has not undergone a review by either the JTRP board or the Indiana Department of Transportation (INDOT). Hence, conclusions presented are only those of the authors.

Use of trade names for various products in this report is for information purposes only, and no official endorsement is implied.

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SUMMARY

On-site treatment of wastewater at highway rest areas poses some unique and different challenges. As a potential alternative, a constructed subsurface wetland system was built at the I-70 rest stop nearby Greenfield, Indiana in 2003. This wetland system, mainly composing of three wetland cells, also includes special cyclic draw-and-fill and recirculation mechanisms to increase oxygen transfer to the wastewater and improve the overall treatment performance. Additionally, a sand mound biofield was also included to test the applicability of final treatment and subsurface discharge.

After several years of system operation, this final report summarizes the overall project experience. The size of Greenfield wetland was found to be sufficient in providing pretreatment that could help avoid potential surcharge from the local treatment plant, but was inadequate for direct on-site discharge. Though the draw-and-fill and recirculation mechanisms provided some treatment benefits, it added to the system operation and raised the construction costs and maintenance needs. The health of wetland plants was identified as a crucial factor in determining treatment performance, and hence sufficient attention should be paid to ensure the proper development of wetland plants. The sand mound biofield did not provide significant treatment, and its use for subsurface discharge depends on the local infiltration capability of soil layers. While constructed wetlands have been touted as low maintenance systems compared to other conventional wastewater treatment approaches, proper maintenance of the wetland facilities was found to be a key factor in achieving optimal performance. The cost analysis showed wetlands to be a viable on-site treatment approach for highway rest areas under favorable conditions, but was still more expensive than the conventional centralized treatment (when they were available).

Based on the experience of Greenfield wetland projects, guidelines of wetland treatment system for highway rest areas were provided, and special challenges were highlighted. Since the use of wetland systems in highway rest areas has not been studied, this report is expected to provide useful information for possible future implementation.

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND AND MOTIVATION

Prior to the mid-twentieth century, most of the industrial and household wastewater was dumped directly into nearby lakes and rivers without proper treatment. As a result, many water bodies became highly polluted and posed a serious threat to public health and safety. To address these concerns, the Federal Water Pollution Control Act (FWCWA) was enacted in 1946, and is the first legislative effort to deal with water quality problems. The act was amended numerous times until it was recognized and expanded in 1972, and formed the basis for the current Clean Water Act (CWA). This act made it unlawful for any person or entity to discharge any pollutants from a point source into navigational waters without a permit. It is because of such legislation that industries and municipalities are required to treat their waste water before discharging into nearby waterways. Since then, waste water treatment plants have become a very important part of our efforts to preserve the environment, and to provide waters that we can use everyday for drinking, swimming, and fishing.

Conventional centralized treatment plants, which treat wastewater using physical, chemical, and biological processes, are known to be energy-intensive, expensive, and with a limited service life not exceeding 30 years (Sundaravadivel and Vigneswaran, 2001). In United States, for small communities (less than 10,000 population), construction costs vary on an average between $10 and $15 billion nationwide (Hammer, 1997). Moreover, complete sewage treatment for all the residents in United States is unlikely, and in some cases undesirable because of geographic, economic and sustainability reasons (Crites and Tchobanoglous, 1998). These reasons apply more to developing countries, where financial constraints are greater due to increased costs incurred because of unreliability of operation and maintenance services. In developing countries, decentralized sanitation in the form of septic tanks is used in all rural areas and in many parts of urban areas as well. Even in developed countries, where provision of centralized sewage treatment exists, decentralized sanitation still plays an important role (Metcalf and Eddy, 1991). In United States alone, more than 60 million people live in homes that are served by decentralized collection and treatment systems (Crites and Tchobanoglous, 1998). Moreover, because of reduction in funding for large sewage treatment systems, many small communities in United States have turned to onsite sewage treatment technologies. All these reasons underscore the need for a continual effort to identify and encourage technologies that provide effective, environmentally friendly, on-site treatment at low cost. One of the low-cost technologies is the use of wetlands for wastewater treatment. In recent times, wetlands have gained popularity over conventional treatment options for small communities, and for businesses located at decentralized locations.

In the past, natural wetlands have received wastewater from many sources, but they have been recognized as a cost effective treatment system only relatively recently. In 1952, perhaps the first experiment to evaluate the possibilities of using wetland plants for wastewater treatment was conducted by the Max Planck Institute in Ploen, Germany. Then, more than 20 years later, the first operational full-scale constructed wetland for municipal sewage was built in Germany. In 1973, United States' first engineered constructed wetland (CW) treatment pilot systems were constructed in Brookhaven National Laboratory near Brookhaven, NY. Since then CWs have been used as a cost effective alternative in treating domestic, industrial, and municipal wastewater and also for storm water management. The goal of CWs is to use the natural treatment mechanisms of wetlands to reduce downstream pollutant discharges. In wetlands, the physical, chemical, and biological processes required for treatment occur in a natural environment instead of synthetic reactor tanks, or basins with artificial chemicals, as in conventional treatment plants. Wetland systems are touted as being low-maintenance technologies, as opposed to conventional treatment plants that require skilled personnel to be present on site. As a result, natural wetlands are often used for treatment of wastewaters. Wetlands are also constructed at desired locations so as to mimic the treatment mechanisms existing in natural wetlands.

Because of the effectiveness of the wetlands at low cost, many developing and developed countries over the last 10 to 15 years have chosen to use them for wastewater treatment for small communities. A wetland system in Tanzania has improved the influent wastewater quality by reducing nitrogen concentration by 70%, chemical oxygen demand by 90%, and almost 100% reduction of total coliform (Mbuligwe, 2005). The final effluent is being used for irrigation. In India, a wetland system that was constructed for a school has successfully reduced the ammonia (66-73%), phosphorus (23-48%), and biological oxygen demand (78-91%) (Juwarkar *et al*., 1995). A number of studies in United States have also shown significant removal efficiency by the wetland system (Steer *et al*., 2005; Huang *et al*., 2000). Wetlands have been found suitable for tropical climates (Kantawanichkul *et al*., 1999), and many European countries have found that wetlands can perform reasonably even in cold climates (Maehlum and Stalnacke, 1999; Maehlum *et al*., 1995; Haberl *et al*., 1995). Other examples can be found in Sundaravadivel and Vigneswaran (2001) and the references therein. These systems use either single or multiple wetland cells for treatment. In multiple-cell systems, each cell might have different treatment objectives, but their combined effect can improve performance over a single- cell system.

Success of wetlands in these and other past studies have prompted the Indiana Department of Transportation (INDOT) to investigate the use of wetlands for the treatment of wastewater generated from highway rest areas. Wastewater treatment from a highway rest area often has some unique characteristics which have long posed significant challenges for highway engineers. So, INDOT undertook a set of three individual “long-range” research projects under the “Wetlands focus area theme” of the “JTRP-INDOT Strategic Environment Focus Area”. The three projects were:

(1) Constructed wetlands (CW) for INDOT rest stop wastewater treatment.
(2) CW systems for wastewater management.
(3) Hydrology of natural and constructed wetlands.

All these projects were developed to facilitate a coordinated experimental evaluation of a full scale, proof-of-concept, constructed wetland of an INDOT rest stop. It was decided to build a new CW at the Greenfield rest stop due east of Indianapolis on I-70. This rest stop is fairly new and was designed by RQAW, Inc. The rest stop toilets have low-flow faucets, consequently generating high strength of wastewater that had to be pumped to the local treatment plant in Greenfield, IN, greater than 3 miles away. The constructed wetland was built with an aim to reduce the pollutant concentrations (mainly ammonia) so that the Greenfield municipal treatment facility would not need to bear this load. This is perhaps the first wetland system in United States that has a network of cells and treats wastewater from a highway rest area. INDOT wants to treat this wetland system as a test site.
To evaluate the performance of different parts of the system, it has been instrumented for flow and water quality measurements. It was hoped that if this wetland was successful in meeting the regulations for various effluents, then the wetland will be used as “reference

wetland" for other rest areas in the state. Moreover, the experience gained at this site could be used for designing and building similar facilities at other sites. The purpose of this report is to provide an assessment of the progress thus far.

1.2 PREVIOUS WORK

Constructed wetlands are of two types: subsurface flow constructed wetlands (SFCW) are designed exclusively for stormwater/wastewater treatment, while the free water surface wetlands (FWS) are commonly used for wildlife habitat and public recreational opportunities. The focus of this section is on SFCW because the Greenfield rest area uses a network of SFCWs.

When a SFCW is used for stormwater treatment, the main objective is to remove total suspended solids (TSS) and heavy metals from runoff. But, SFCWs for wastewater treatment are expected to remove not only TSS and heavy metals, but also fecal coliforms, biochemical oxygen demand (BOD), chemical oxygen demand (COD), ammonia-nitrogen (NH_3-N), and phosphorus (P) from wastewater. The designs of SFCWs are dictated by treatment objectives. Wetland performance depends on factors like:

- Wetland soil type, soil chemistry, and the kind of reactions that occur between the soils and the contaminants.
- Operating water depths, hydraulic loading rate, physical configuration of the wetland systems (Wieder *et al*., 1989).
- Contaminant uptake by vegetation (Watson and Hobson, 1989).
- Hydrology and hydraulic design of the wetland (Kadlec, 1989; Owen, 1995; Persson and Wittgren, 2003).

Wetland systems are usually designed to provide primary treatment to the wastewater stream through a single or multiple septic tanks or facultative ponds before the wastewater flows into the wetland systems. It has been found that wetlands are efficient in removing fecal colliforms, BOD, COD, and TSS (all around 90%) although showing low efficiency in NH_3-N (50-60%), and P (25-45%) removal (Juwarkar *et al*., 1995; Kantawanichkul *et al*., 1999; Platzer, 1999; Manios *et al*., 2003; Mbuligwe, 2005; Steer *et al*., 2005). However, high removal rate of BOD, COD is influenced by organic loading rate (Persson and Wittgren, 2003). With high loading rate, removal efficiency of BOD, and COD can even decrease to 70%. Unfortunately, not all studies cite influent organic loading rates.

Another important factor influencing removal rate is how the influent is fed into the wetland system by vertical flow or by horizontal flow. Systems with horizontal flow can remove BOD, COD, TSS, and fecal coliforms significantly, but tend to have very low NH_3-N, P removal efficiency (Juwarkar *et al*., 1995; Mbuligwe, 2005; Steer *et al*., 2005). On the other hand, systems with vertical flow show high percentage of removal of NH_3-N (Kantawanichkul, 1999). Studies have shown that a combination of both types of flow is better than only vertical flow or only horizontal flow systems (White, 1995; Maehlum *et al*., 1995; Platzer, 1999). This is because vertical flow systems provide aerobic environments to enhance nitrification and horizontal flow systems provide anaerobic subsurface flow environments for denitrification, and nitrogen removal requires both the processes.

Pollutant removal efficiency is also influenced by the type of media used in the cell. Studies show that gravel beds with gravel sizes between 5-30 mm are better to allow for roots to develop and offer sufficient surface area for physical, chemical, and microbiological processes to occur unhindered (Manios *et al*., 2003). Most studies showed that plants played little or no role in treatment. However, one study found that planted wetland cells had much greater removal efficiency than unplanted wetland cells (Juwarkar *et al*., 1995). In some systems, a portion of the effluent is recycled back to improve treatment efficiency. The percentage of effluent recycled back is also an important factor. White (1995) had studied 3 wetland systems where 0%, 100%, or 200% effluent was recycled back as the influent, and found that the system recycling 100% effluent was more effective than systems recycling 0%, or 200% effluent.

Wetland modeling efforts have ranged from attempts to describe very specific wetland processes to detailed models of wetland hydrology and nutrient cycles. Mitsch (1983) classified wetland models into seven categories: (1) energy/nutrient models; (2) hydrological models; (3) spatial ecosystem models; (4) tree growth models; (5) process models; (6) causal models; and (7) regional energy models. Again, models that are developed for wetlands are very site and application specific, and models results have not been easily transferable.

Almost all models treat wetlands as an ideal plug-flow reactor or a continuously stirred tank reactor (CSTR), with the former being more popularly used. The models assuming ideal plug-flow behavior tend to overestimate the removal efficiency (Dahab *et al*., 2001). Assumption of ideal plug flow behavior implies that all the particles in the liquid advance in the tank or reactor with equal velocity while in case of CSTR all the particles in the liquid are perfectly mixed, and inflow and outflow rates are same. The CSTR models show some degree of success (Kadlec, 1994; Kadlec and Knight 1996). However, wetland hydraulics is neither completely plug-flow nor CSTR. In reality, a wetland behaves somewhere between the two extremes. So, it is better to model wetlands as a combination of plug-flow reactor along with a number of continuously stirred tank reactors (Kadlec and Knight, 1996).

Wynn and Liehr (2001) developed a mechanistic model that simulates hydraulic behavior of a wetland by CSTR approach. They calibrated the model using the data from a constructed wetland in Maryland. The model requires estimation of 15 initial conditions and knowledge of 42 parameters which is not a convenient task. Recently, Martinez and Wise (2003) used United States Geological Survey's (USGS) one dimensional transient inflow and outflow model (OTIS) in 17 Orlando Easterly Wetland cells to analyze wetland hydraulics. The transient model combines plug flow with dispersion equations, and the model results were found to agree well with field data. The model was calibrated first using tracer test results. Tracer test is a simple and often used tool for hydraulic analysis. Usually, a tracer is injected at the inlet of the system and collected at the outlet. The Greenfield wetland system is a rather complex network of 3 wetland cells with recirculation, and includes septic tanks and lift stations. Fig 1.1 shows a site plain view of this complex. A detailed hydraulic analysis of this system would be very complicated. So, a simple tracer test may not suffice to evaluate the performance of all units of the system. This hydraulic complexity necessitated the development of a separate model for the Greenfield wetland system.

1.3 SCOPE OF THE REPORT

In Chapter 2, wetland types and factors that need consideration for wetland design are briefly discussed. Chapter 3 provides a detailed description of the Greenfield wetland system. Chapter 4 describes the hydrologic model of the Greenfield wetland system, and

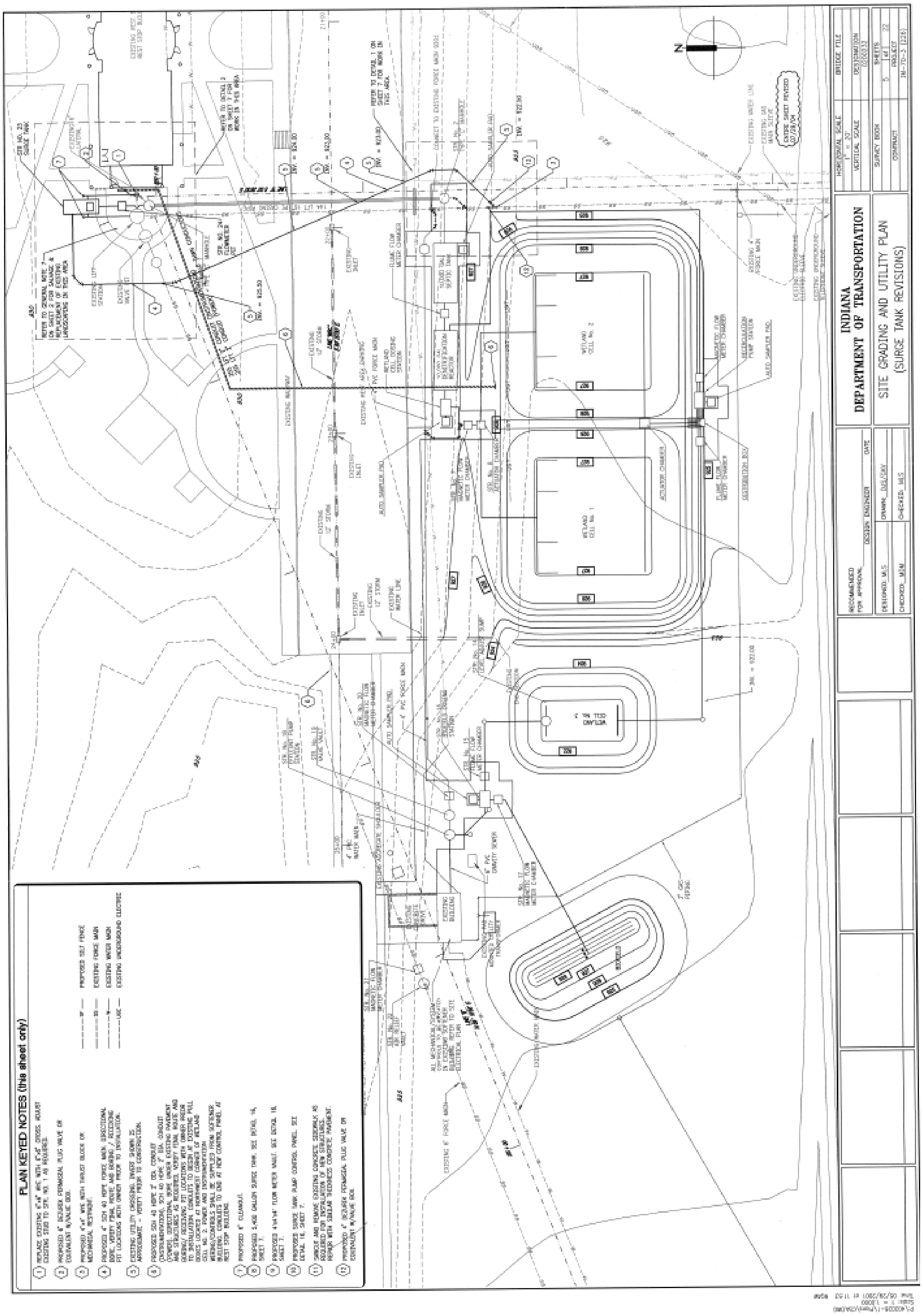


Figure 1.1 – Plan view of the wetland complex at the Greenfield Rest Stop on I-70

focuses on how the model was built and presents results for model corroboration. Chapter 5 denotes the various experimental methods used to collect data. Chapter 6 discusses the importance of wetland plants. A literature review is included in this chapter. Chapter 7 discusses wetland treatment performance, where hydraulic and environmental data are analyzed and presented. An analysis of wetland plant performance is also included. Chapter 8 discusses the lessons learned thus far. General guidelines for adopting waster water treatment wetlands in highway rest areas are provided in Chapter 9. Conclusions of this project and guidelines for future implementation are presented in Chapter 10. Appendix A contains a case study that supplements the research presented herein, with particular relevance to wetland plants. Appendix B lists a complete project timeline highlighting important dates, project meeting notes, and significant wetland activities.

CHAPTER 2

BASIC CONCEPTS AND DEFINITIONS IN WETLANDS

2.1 DEFINITION AND CLASSIFICATION OF WETLANDS

Wetlands are also known as slough, brackish marsh, freshwater swamp, and ponds (Hammer and Bastian, 1989; Persson and Wittgren, 2003). Wetlands can be defined as vegetated land areas that are wet during part or all the year, with the water surface in the wetlands near to the ground keeping the soil saturated (US EPA, 1988; Kadlec and Knight, 1996). The committee on Wetland Characterization defined wetlands as:

> ".. an ecosystem that depends on a constant or recurrent, shallow inundation or saturation at or near the surface of the substrate. The minimum essential characteristics of a wetland are recurrent, sustained inundation or saturation at or near the surface and the presence of physical, chemical, and biological features…. Common diagnostic features of wetlands are hydric soils and hydrophytic vegetation except where specific physicochemical, biotic, or anthropogenic factors have removed them or prevented their development."

Wetland soils lack oxygen as a result of being saturated for extended periods. For annual vegetation production, the soils typically contain a high proportion of organic matter. Because of anaerobic conditions and presence of thick litter layer, wetland soils provide an environment where several chemical and microbial processes can thrive. Wetlands provide ideal conditions for a wide variety of microorganisms which are the "workhorses" in the wetland treatment processes.

Hammer (1997) classified wetlands into five different groups based on various criteria. These are:

<u>Natural Wetlands</u>

These are the wetlands where the substratum is periodically flooded throughout the year. Some wetlands support a variety of plants and animal species. They are considered waters of the U.S. and are subject to discharge regulations.

Constructed Wetlands

These wetlands are created from non-wetland sites, with the primary purpose commonly being wastewater treatment. Constructed wetlands treat wastewater by chemical, biological, and physical processes that are typical of natural wetlands. Physical entrapment and sedimentation of wastewater solids are also key processes aiding the removal of pollutants. Constructed wetlands themselves are not considered waters of the U.S. Discharges from constructed wetlands into the waters of the U.S. are regulated, and must adhere to NPDES permits.

Created wetlands

These are wetlands created to replace destroyed habitat on site or elsewhere. They are considered waters of the U.S., and are subject to discharge requirements.

Restored Wetlands

Several areas existed as natural wetland systems in the past, but were altered in such a manner as to eliminate typical flora/fauna species. Subsequently, original conditions were reinstated in some instances creating conditions for natural flora/fauna to return to the system. These are called as restored wetlands, and are waters of the U.S. that are subject to discharge regulation.

Floating Aquatic Systems

These are systems that support fully floating vegetation such as water hyacinth (*Eichhornia spp*) and duckweed (*Lemna spp*). They are subject to NPDES permitting regulations.

Constructed wetlands are further classified into two groups: free water surface systems (FWS), and subsurface flow constructed wetlands (SFCW). These are described briefly.

Free Water Surface (FWS) Systems

FWS systems are designed as a basin to simulate natural wetlands. In this system, water is generally introduced above the ground surface, is open to the atmosphere, and then it flows through the wetland. The depth of water in the wetlands varies from 6 to 12 inches. The wetlands are typically divided into cells by using earthen berms, concrete, or wood to ensure smooth flow and maximum contact between water and wetland plants. FWSs are frequently used to maximize wetland habitat values and reuse opportunities while improving water quality. Figure 2.1 shows a typical FWS system.

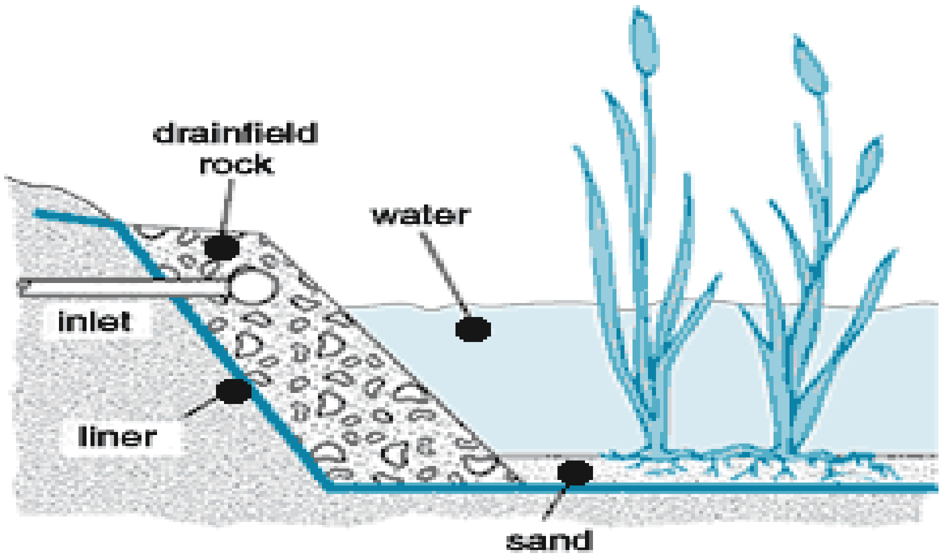


Figure 2.1 – Profile view of a free water surface wetland
(Source: http://www.extension.umn.edu/distribution/naturalresources/DD7671.html)

Subsurface Flow Constructed wetland systems (SFCW)

SFCWs are usually shallow gravel beds where water passes horizontally below the ground surface across the bed. Therefore odors, and other nuisance problems that are common in FWS wetlands are generally eliminated in SFCWs. Typically soil, sand, gravel, or crushed rocks are used to create this permeable medium that may be as much as 4 feet thick from the ground surface. The extensive root system growing in the gravel media provides a substrate for microbial communities responsible for pollutant reduction. Typically, these wetlands use impermeable liners to prevent groundwater contamination. SFCWs are designed and operated to improve water quality. Figure 2.2 shows a typical SFCW system.

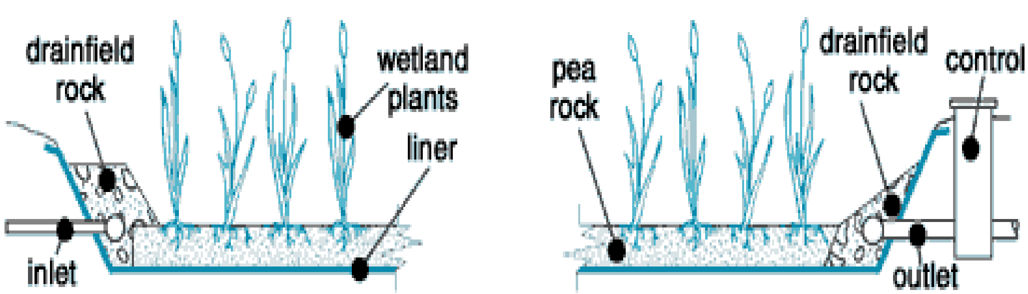


Figure 2.2 – Profile view of Subsurface Flow system
(Source: http://www.extension.umn.edu/distribution/naturalresources/DD7671.html)

It is believed that there are other benefits offered by SFCWs when compared to FWSs. Because of the porous media used in SFCWs, they offer more surface area for treatment than FWS systems. As a result, treatment efficiency is higher. In addition, there is better thermal protection within SFCWs so that bacterial activity may continue at deeper locations of the wetland even during cold weather.

2.2 HYDROLOGIC FACTORS RELATED TO WETLANDS

Important components of wetland hydrology are precipitation, infiltration, evapo-transpiration, water depth, and hydraulic loading rate. Kadlec and Knight (1996), Watson and Hobson (1989), Kadlec (1989), and Mitsch and Gosselink (1993) discussed wetland hydrology to varying degrees of detail. Some of the common terms and concepts associated with wetland hydrology are:

Hydraulic Loading Rate

Under steady flow conditions, hydraulic loading rate (HLR) is defined as:

$$\text{HLR} = \frac{q}{A} \tag{2.1}$$

where q is the inflow rate (L^3/T), and A is the wetland area (L^2). Wetland inflows are time varying, so the HLR definition must be treated as a long term time average. For constructed wetlands, HLR varies from 0.6 to 7.0 cm/day (Wood, 1995).

Water depths

Wetlands are wet during a large fraction of the time. This water is important for the wetland to function properly. In natural wetlands, water depths cannot be controlled and any part of the wetland may be wet at a given time. But in constructed wetlands, the bottom is generally leveled so as to ensure a certain water depth over the entire wetland area. For natural surface wetlands, the average water depth is:

$$\overline{h} = \frac{1}{A}\iint_A h(x,y)\,dA \tag{2.2}$$

where $h(x,y)$ is the depth of wetland at the coordinates (x,y), and A is the total area. For subsurface constructed wetlands with time varying flow rates the average depth over time t is defined as:

$$\bar{h}(t) = \int_0^t \frac{q(\tau)}{\eta A} d\tau \tag{2.3}$$

where A is the area of the wetland from the plan view (L^2), q is the flow rate (L^3/T) into the wetland, and η is the porosity of the bed material. For constructed wetlands, an accurate estimation of η is difficult because this value may change with time based on vegetation growth.

Hydraulic Retention Time

Nominal hydraulic retention time is defined as:

$$\tau = \frac{\hat{V}}{q} \tag{2.4}$$

where $\hat{V}$ is the volume of the wetland (L^3) that can be occupied by the wastewater. Because of the transient nature of inflow and outflow, a constant retention time cannot be easily estimated.

Volumetric balance

If the wetland is considered as a single system, and assuming no changes in the density of the water, the volumetric flow rate equation is

$$\frac{d\hat{V}}{dt} = q_i(t) - q_o(t) \tag{2.5}$$

where $q_i(t)$ and $q_o(t)$ are inflows and outflows of the wetland, respectively.

Hydrologic Budget

For a constructed wetland, a simplified hydrologic budget can be expressed by a more detailed volumetric flow equation as (US EPA, 1988):

$$q_i(t) - q_o(t) + P(t) - ET(t) = \frac{d\hat{V}}{dt} \tag{2.6}$$

where $P(t)$ and $ET(t)$ represent all the precipitation to and evapotranspiration from the wetland system, respectively. These contribute to change in the volume of water in the wetland system with time, $\frac{d\hat{V}}{dt}$. The ground water recharge and discharge are not included in (2.6) as most constructed wetland systems have a liner or impermeable barrier at the bottom (Kadlec and Knight, 1996). However, it is difficult to estimate certain hydrologic components such as evapotranspiration. The water budget in equation (2.6) is a lumped-modeling approach. For a more detailed modeling of wetland hydraulics, compartmental models, such as FWETMOD (Earles, 1999) are used.

Two major hydrologic parameters - the hydraulic retention time (HRT) (also known as hydraulic residence time) and permeability of the wetland media have the greatest influence on water treatment performance (Ranieri, 2003). Actual hydraulic residence time can be found by the following relationship:

$$\tau = \frac{\hat{V}_{eff}}{Q} \tag{2.7}$$

where τ is hydraulic retention time (T), $\hat{V}_{eff}$ is the actual volume (L^3) of the wetland that can be occupied by water and is usually expressed as $\eta \hat{V}_{bulk}$, η is the effective porosity and $\hat{V}_{bulk}$ is the bulk wetland volume. Martinez and Wise (2003) have shown that η can be estimated using tracer test data. On the other hand, Thackston *et al*. (1987) have carried out experiments on a number of shallow ponds of sizes varying from 60 to 60,000 m^3 and developed an equation for η that depends on the length L and width W of the wetland only. The Thackston *et al*. equation is:

$$\eta = 0.84\left[1 - e^{-0.59(L/W)}\right] \tag{2.8}$$

Equation (2.8) is an empirical relationship that does not consider the time varying nature of inflows and outflows affecting the value of $\hat{V}_{eff}$. In (2.7), Q is the constant flow rate through the system (US EPA, 1988; Watson and Hobson, 1989). The HRT defined in (2.7) increases with an increase in the total volume of the wetland system or a decrease in the hydrologic flow rate. The HRT in estimate (2.7) is a gross average measure.

2.3 ENVIRONMENTAL FACTORS IN WETLAND TREATMENT

Wetlands treat wastewaters by biological, physical, and chemical processes that depend on the surface area of the bed material, and the opportunity time for reactions to go to completion. So, a first step in designing a wetland is to determine a size to meet the discharge requirements. But available land is often a limiting factor. Kadlec and Knight (1996) recommend that a reasonable size of the wetland can usually be determined using

(1) Historical data
(2) Microbial Growth model
(3) Areal and volumetric loading rate

Historical data

Empirical data collected from pilot scale and fully operational treatment wetlands are used to determine the size required to meet the treatment goal. In this case, the data can only be used from wetlands with similar type of operational and climatic conditions.

Microbial growth model

Conventionally, a horizontal plug flow model has been used to design the wetland treatment systems, and it is assumed that microorganisms in the wetlands follow first order reaction kinetics. The first order kinetics model is

$$C_t = C_0 \exp^{-kt} \tag{2.9}$$

where C_t is the effluent pollutant concentration at time t, and C_0 is the influent pollutant concentration at time $t = 0$. The constant k in equation (2.9) is a first-order reaction-rate constant that depends on temperature, and t is time often taken as hydraulic retention time τ. The reaction rate constant k in equation (2.9) can be found using the Arrhenius equation that is:

$$k = k_{20} \Theta^{T-20} \tag{2.10}$$

where k_{20} is the first order reaction rate constant at temperature of $20^\circ\mathrm{C}$, Θ is the empirical temperature coefficient, and T is the actual temperature ($^\circ$C).Some commonly used k_{20} and Θ values can be found in Table 2.1 (adopted from Reed *et al.*, 1995).

Table 2.1 – Commonly used temperature coefficients Θ and rate constants k_{20} for subsurface wetland

	Θ	k_{20}
BOD	1.060	1.104
Nitrification	1.048	0.411
Denitrification	1.150	1.000

(Adopted from Reed *et al.*, 1995)

Areal and volumetric loading rate

Existing wetlands can be used as a model to determine the size of new wetland systems. Relationships between volume of water or mass of pollutants introduced in a system, its volume, and its surface area can be developed and used as a guideline for new systems. This type of method does not involve depth of the wetland and temperature of the system.

Once the size of the wetland is determined using one of the above methods, the wetland is then designed to limit the discharge of pollutants to meet regulations. Generally, a wetland treatment system primarily works like a biological filter and is expected to reduce the following:

Biological Oxygen Demand (BOD)

BOD is a measure of the amount of oxygen the wastewater will consume during biological decomposition processes. Commonly, oxygen consumed in five days is used as a measure of BOD, and is known as BOD_5. The higher the difference of the influent and effluent BOD_5, the better is the performance of the treatment system.

Total Suspended Solids (TSS)

TSS includes both organic and inorganic particles. Most of the removal in the wetland occurs within the first few meters beyond the inlet under quiescent conditions. Controlled dispersion of the effluent flow can help to keep the velocity low to allow solid settling. A high concentration of suspended solids in the receiving water creates turbidity, which can further impede functions of aquatic life. Most wetland treatment systems are over-designed with respect to TSS removal, since treatment of other contaminants governs wetland design.

Nitrogen

Nitrogen (N) is a major component of municipal wastewater, storm water runoff from urban and agricultural lands, and wastewater from various types of industrial processes. Nitrogen can exist in a variety of forms in the environment, and can transform to other forms rapidly and frequently. Discharge of excessive amount of N causes environmental and health problems. Municipal and industrial wastewaters usually contain a significant amount of both organic and inorganic forms of N. Organic nitrogen is typically associated with wastewater solids or algae. Inorganic nitrogen can exist in the form of ammonia, nitrate, nitrite, or nitrogen gas. Ammonia is easily captured by the clay particles in soil, whereas nitrates will move directly to groundwater. Therefore, as a design principle, nitrogen in the effluent at an on-site treatment system is preferred in the form of ammonia rather than nitrate. Much of the organic nitrogen will undergo decomposition or mineralization within the system. Inorganic nitrogen is formed as a result of biological nitrification and denitrification reactions.

Substantial removal of N in the wetland may occur through the settling of particles containing N in the influent. In addition, since N is an essential plant nutrient, it can be removed through plant uptake of ammonium or nitrate and stored in organic form in wetland vegetation. Ammonium may be chemically bound in the soil on a short-term basis, while organic N from dead plant material can accumulate in the soil as peat, a long-term storage mechanism.

Phosphorus

Phosphorus (P), like N, is a major plant nutrient; hence addition of P to the water bodies can lead to noxious algal blooms. The primary mechanisms for removal of phosphorus in wetland systems are chemical precipitation and adsorption by the soil matrix. The degree of phosphorus removal in a wetland is dependent on the amount of contact time between the wastewater and the soil matrix.

The key to long-term success of a wetland system depends on understanding and controlling the behavior of the wastewater as it flows through the wetland. Wetland hydraulics refers to the physical mechanisms of conveying the water. In constructed wetlands, hydraulics plays a very important role in influencing the hydrology of the system. According to Persson and Wittgren (2003), several design aspects can influence hydraulic conditions in wetlands. These are:

- Profile (topography), i.e., flat or angled bottom
- Berm (topography)
- Island (topography)
- Depth
- Length to width ratio (horizontal plane)
- Meandering (horizontal plane)
- Form (horizontal plane), i.e., curved, circular, triangular or rectangular shape
- Baffles
- Inlet and outlet
- Vegetation, i.e., plant characteristics, density, location

Persson *et al*. (1999) studied 13 hypothetical ponds to investigate influence of pond shape, inlet/outlet location, and inlet/outlet type. Their study showed that ponds with baffles, or spread inlet, or long elongated shapes provided good hydraulic efficiency. They have defined hydraulic efficiency λ by the following equation

$$\lambda = \frac{t_p}{t_n} \tag{2.11}$$

where t_p is the time of peak outflow concentration, and t_n is hydraulic retention time as defined in equation (2.4). Ponds showing $\lambda > 0.75$ are considered to have good hydraulic efficiency.

CHAPTER 3

GREENFIELD WETLAND SYSTEM

3.1 PROJECT BACKGROUND

Wastewater treatment from a highway rest area has some unique characteristics which have long been challenges for highway engineers. Some of these are (Chan *et al.*, 2004):

(1) *Remote location* – Rest areas are often located in remote locations, which make centralized treatment inconvenient. Sewage lines, several miles long, are needed specifically for the rest area, which in most cases are challenging and not economical. Hence, onsite wastewater treatment is preferred.

(2) *High strength of wastewater* – The wastewater from rest areas originate mostly from toilets. Since low flush toilets and flow restrictive faucets are adopted in most Indiana highway rest areas to conserve water, the end result is concentrated wastewater with high biological oxygen demand (BOD) and nitrogen. This raises difficulties for onsite disposal, and is even unfavorable for conventional treatment.

(3) *High variability in wastewater flow* – During peak traffic hours and holidays, rest area usage increases because of an increase in traffic volume, which generates high wastewater flow. On the other hand, during slack periods, the wastewater flow is a small percentage of the peak flow. This high variability in the flow rate puts stress on the wastewater treatment system even if the system has been designed for a high discharge rate.

(4) *Limited Personnel* – Any conventional wastewater treatment system requires constant monitoring and maintenance. However, because of budget constraints, there is usually a lack of manpower in rest areas to ensure their optimum performance.

The Greenfield rest area due east of Indianapolis on I-70 was built fairly recently (see Figure 3.1 for location). This rest area faces all the common problems of other highway rest areas, along with some unique ones. This rest area was connected directly with a greater than three-mile long sewer line to the municipal wastewater treatment plant of the city of Greenfield. From personal communication from INDOT engineers, it was found that the wastewater takes on average three to four days to reach the lift station of the treatment plant. As a result of this long residence time, the nitrates in the wastewater turn into ammonia in absence of oxygen. Further, the strength of the wastewater is increased by use of low flush toilets and flow-restrictive faucets that were installed to conserve water in the rest stop. There is a possibility that the city of Greenfield may impose surcharges in addition to the sewage bill as a result of the increased concentration of BOD and ammonia. The wastewater was also causing an odor problem at the city's lift station.

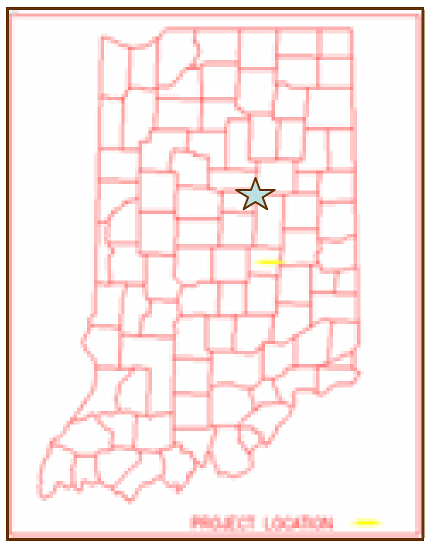


Figure 3.1 – Location of the wetland system

In order to address the problems, a subsurface constructed wetland system was built in 2003 at the rest area site to provide pretreatment on site before discharging the wastewater to the municipal sewer. The wetland system was made operational from early 2004. This specific system was built to see if wetlands could serve as onsite treatment facilities for rest areas.

The rest area was designed to treat an average flow rate of 5,000 gallons per day. The treatment system would receive wastewater generated from two separate buildings situated at opposite sides of the east and westbound lanes, respectively (Figure 3.2). This wastewater treatment and disposal system was proposed by *RQAW* and *J. F. New and Associates*. The evaluation of this project is described in the Appendix at the end of the report.

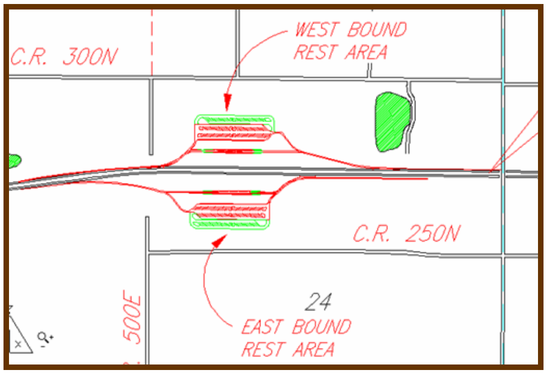


Figure 3.2 – West and Eastbound rest areas

3.2 TREATMENT SYSTEM DESIGN

The treatment system includes three wetland cells and a biofield (Figure 3.3). The wetland cells were expected to provide pretreatment to reduce BOD and nitrogen concentration. The biofield at the tail end of the treatment system was to provide further treatment and work as a subsurface disposal system. The biofield was added to see if subsurface disposal of wetlands effluent was possible.

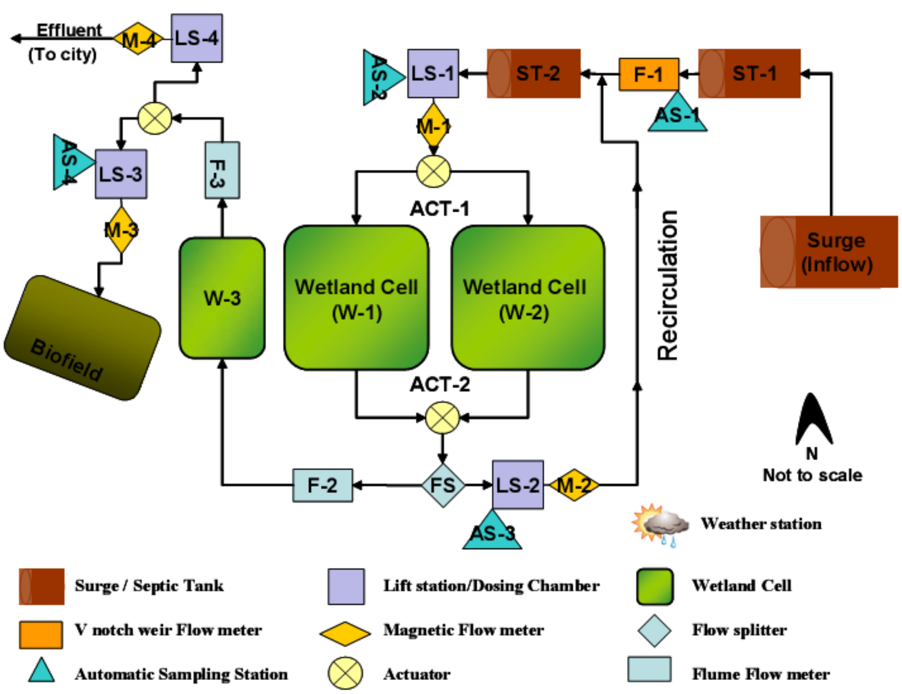


Figure 3.3 – Schematic of the Greenfield wetland system

The arrows in Fig. 3.3 indicate the direction of wastewater flow in the system. Wastewater from the north rest stop (gravity feed) and south rest stop (pump feed) are collected and sent to the surge tank, pump to the first septic tank, ST-1 and almost immediately sent to the second septic tank ST-2. The wastewater from the second septic tank flows to a lift station LS-1. Water is pumped to an actuator, ACT-1 that directs the wastewater to either of the two parallel wetland cells W-1 and W-2. Another actuator, ACT-2 at the tail end of the parallel wetland cells signals when the cells will be drained. The water is then directed to a flow splitter box FS. A part of the drained wastestream is recycled back to second septic tank by the pumps in LS-2, and the remainder of the wastewater flows to the third wetland cell W-3. Part of the wastewater from the third wetland cell is directed towards the biofield with pumps in LS-3 controlling the dosing, and the remaining wastewater is pumped by LS-4 to Greenfield's municipal wastewater treatment plant. In Fig. 3.3, AS-1 to AS-4 are automatic samplers, F-1 to F-3 are open channel flow meters, while M-1 to M-4 are magnetic flow meters. The following sections describe each component of the wetland system.

3.2.1 SEPTIC TANKS

Two septic tanks ST-1 and ST-2 are placed in a series (see Figure 3.4) to provide primary treatment to the influent wastewater. The tanks were designed to remove and digest complex organic solids from entering the wetland cells.

The tanks are also designed to remove suspended solids and begin breakdown of the complex organics in the wastewater. In addition, there is a filter at the outlet of the second septic tank ST-2, to remove large inorganic solids that would otherwise clog wetland units.

The two tanks have a similar size and are capsule shaped. The maximum diameter of each tank is 8 ft with a length of about 31.5 ft. The capacity of each of the tanks is 10,000 gallons (37,850 L). The inlet and outlet pipes are 6 inches in diameter, and are placed at a height of 7 ft from the bottom of the tank.

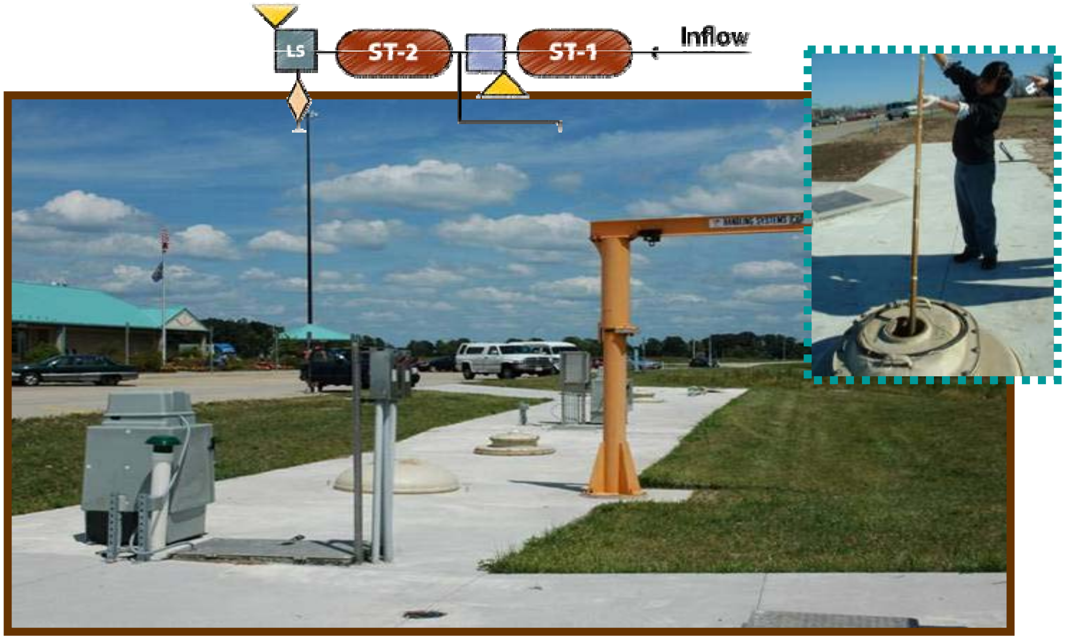


Figure 3.4 – Septic tanks ST-1 and ST-2. Inset shows T. P. Chan using the 'sludge-judge' to estimate the quantity of the solids deposited in the septic tanks.

3.2.2 SUBSURFACE WETLAND SYSTEM

The wetland system has two parallel wetland cells, W-1 and W-2, designed to provide secondary treatment (see Fig. 3.3). These two cells are similar, with base area of 56 ft by 56 ft and a depth of 3 ft, and with a side slope of 1 to 3.

The cells have two distinct sections - a front and a back section. At the front (inlet) end, an elevated gravel mound covers the influent manifold system that distributes wastewater evenly across the front section of the cell (Figure 3.5). The manifold is located above the water level in the cell, and allows wastewater to trickle down the gravel medium and therefore acts as a vertical filter. The purpose of this vertical filter is to increase oxygen transfer and promote nitrification. Biochemical Oxygen Demand (BOD) is partially removed in this section.

The middle portion of the wetland is vegetated and a minimum water level is constantly maintained. The bottoms of the cells are filled up to a depth of 30 inches with 1-inch to 3-inch screened and washed river gravel, mixed with 10% washed limestone. During reactions, hydrogen ions are released thereby increasing the pH of the system. Therefore, limestone was added to provide alkalinity, and maintain a neutral pH in the system. Thus, the removal efficiency of the cell is improved. At the top of this gravel layer, pea gravel (3/8 inches screen, washed gravel) is filled up to a depth of 6 inches. The top of the midsection is filled with peat up to a depth of 6 inches. The vegetated top and porous medium in the bottom provide denitrification and further reduction in BOD through biological processes. A subsurface effluent manifold is located at the outlet end near the bottom of each cell to collect and discharge the effluent. Figure 3.6 provides a view of the two parallel wetland cells.

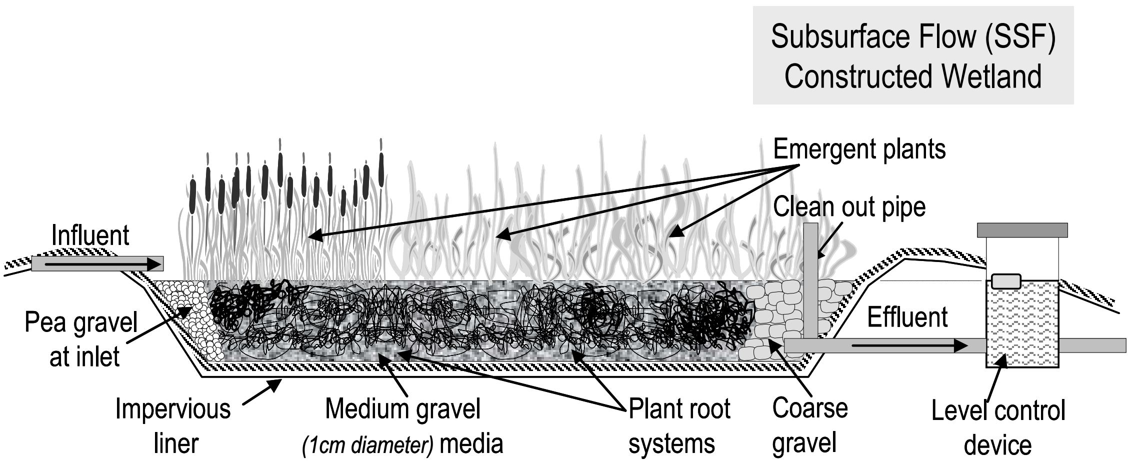


Figure 3.5 – A typical subsurface flow constructed wetland

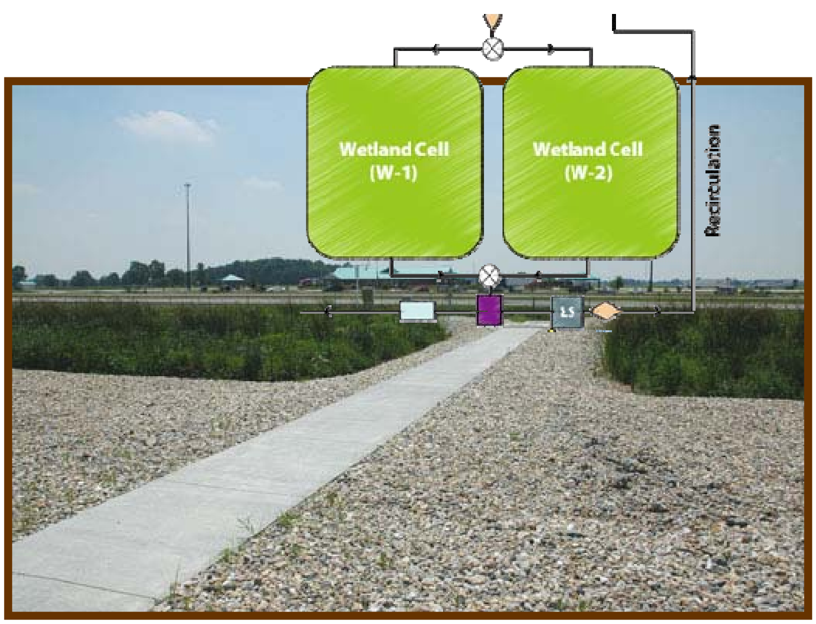


Figure 3.6 – Two parallel wetland cells, W-1 and W-2

There is a third wetland cell W-3 designed to further treat the wastewater before it connects to the Greenfield sewer (see Figure 3.7). This cell serves as a polishing unit. This wetland is 20 ft. by 40 ft. in size (along the direction of flow). The sides of the wetland are sloped at 1 to 3. This wetland has a smaller depth (2 feet) than the parallel wetlands. The front and back sections are similar to the parallel cells. In the middle section, 1 to 1 ½ inches of gravel with 10% limestone is used to fill up to a depth of 18 inches. At the top, pea gravel is used to cover a depth of 6 inches. Peat moss is used to cover the top of the wetland to a depth of 3 inches. Although treatment wetland beds are usually slightly sloped to allow a horizontal flow, the Greenfield wetlands have a horizontal bed and work like large storage buckets.

Figure 3.7 - Third wetland cell, W-3

3.2.3 WETLAND MEDIA

Three different types of screened, river-washed gravel are used as wetland medium. A larger size of 1.5 to 3 inches gravel is used in the front section of the parallel wetlands in order to reduce the potential of clogging. A smaller size of 1 to 3 inches gravel is used in the middle section of the parallel wetlands. The front section of the polishing wetland is filled with 1 to 3 inches of gravel, but the middle section is filled with 1 to 1 ½ inches of gravel. Pea gravel is on the top of the middle section to support vegetation growth. The pea gravel layer is laid at 6 inches thickness. An additional thin layer (3 to 6 inches) of peat moss is placed on top of the pea gravel to provide thermal insulation over the winter months. All the gravel used is mixed in with 10% crushed limestone (by volume) to ensure adequate alkalinity for nitrification. The bottom of the wetland cells is lined with EPDM liners especially designed for pond liner application. Figure 3.8 shows different type of wetland gravels.

Figure 3.8 – Wetland media

3.2.4 DOSING TANKS

The wetland system has one surge tank and four dosing tanks or lift stations at different locations in the system (see Fig. 3.3). The surge tank is located at the inflow part of the entire system collecting wastewater from both north and south part of the rest stop. The first dosing tank, LS-1, doses the parallel wetlands, W-1 and W-2. LS-1 receives inflow from the second septic tank, ST-2. The second dosing tank, LS-2, is placed following W-1 and W-2. LS-2 re-circulates part of the treated wastewater from W-1 and W-2 to ST-2. Dosing tank, LS-3, after the third wetland cell, transmits a portion of the wastewater to the biofield. The fourth dosing tank, LS-4, pumps wastewater from the third wetland cell back to the main westbound lift station, from where it is finally sent to the Greenfield wastewater treatment plant.

Gravity flow exits from ST-2 to LS-1, from the two wetland cells to LS-2, and from W-3 to LS-3. Each of the lift stations have a cross-sectional area of 8.5 ft by 5.5 ft with a depth of 7 ft. Each lift station is equipped with two pumps. The pumps used in the lift stations are duplex pumps. Except for LS-3 being controlled by the SCADA system, the rest pumps operates on a level float control system. Wastewater inflow to these lift stations is not the same, and the level floats are set at different heights in each lift station to accommodate varying flow rates. For example, in LS-1, the ON/OFF floats within the tank are separated by a vertical elevation of approximately 24 inches that translates to 700 gallons per dose. The number of doses required will vary based on actual daily flow rate, precipitation, and recycle percentage.

The pumps in the LS-1 have a capacity of 50 gpm (gallon per minute). An alarm is set approximately 6 inches above the ON float to signal the failure of the pump in the lift station. A lag is set above the alarm to initialize an “All ON” condition to ensure that the alternate pump functions while the other pump is out of service.
The wastewater flows from W-1 and W-2 to the distribution box that serves as a flow splitter (FS in Fig. 3.3 and see Figure 3.9) from where 83 percent of the influent is directed to the recirculation dosing tank, LS-2. The recirculation percentage can be adjusted by plugging holes in the distribution box. The ON/OFF floats in LS-2 are separated by an approximate height of 30 inches that provides 875 gallons per dose. The pumps have a capacity of 50 gpm.

Figure 3.9 – Flow splitter FS

The rest of the 17 percent of the wastewater from the distribution box flows by gravity to the third wetland cell, W-3. There is a level adjust sump at the end of the wetland that controls flow out of the cell into the biofield lift station, LS-3. The pump within LS-3 needs to dose a small amount of water. Initially it was approximated as 100 gallons to the biofield on a timer-activated cycle at a frequency of four times a day - a total of 400 gallons per day. Between the two floats in the tank, the OFF float prevents the pump from running dry in the event of manual pumping, while the other float works as an alarm to the pump indicating high water in the tank. The floats are separated by approximately 39 inches.

The biofield lift station, LS-3, overflows to the fourth lift station, LS-4. Pumps within LS-4 lift the treated water and send it through the force main to the original lift station that pumps water to the wastewater treatment plant. The floats within the LS-4 dosing chamber are separated by 18 inches. LS-4 is expected to dose 64 times a day for a total of 9000 gallons.

3.2.5 BIOFIELD

At the tail end of the wetland system, a biofield was constructed to provide treatment to a small amount of wastewater (see Figure 3.10). The biofield is essentially a sand mound with the top seeded with prairie grass. It has a base area of 1652 square feet with a bed area of 333 square feet. The biofield was expected to treat the wastewater by denitrification, and finally dispose the treated effluent by evapotranspiration and infiltration to the subsoil.

Figure 3.10 – Biofield

3.2.6 WETLAND PLANTS

Wetland plants provide storage sites for carbon and nutrients and play a role in the movement of gases to and from the wetland substrate. Oxygen is transported from the air through the plant into the root zone. This ensures that aerobic respiration can be maintained in the non-photosynthetic portion of the plant tissues buried in the anoxic substrate. Recent research has shown that wetland plants do not increase oxygen transfer significantly and, thus, contributions in the treatment process are not substantial (Juwarkar *et al*., 1995, Huang *et al*., 2000). However, the wetland plants are still considered an important part of the system as they (1) increase the rate of water loss through evapotranspiration, (2) provide a large surface area for bacterial growth through an extensive root system, and (3) provide aesthetic value to the treatment facility.

About 3,280 plants of 13 different species were planted in the three wetland cells. To promote diversity and maintain aesthetic value, a variety of perennial bulrushes, sedges, grasses, and a number of flowering species were planted. Examples are shown in Figure 3.11. More details are available at the website (https://engineering.purdue.edu/Research Groups/Wetland) Wetland plants are discussed in more detail in Chapter 6 of this report.

Figure 3.11 – Examples of wetland plants (Left panel: Scirpus Cyperinus [wool grass] ; Right panel: Helenium Autumnale[Sneezeweed])

3.3 WETLAND OPERATION SCHEME

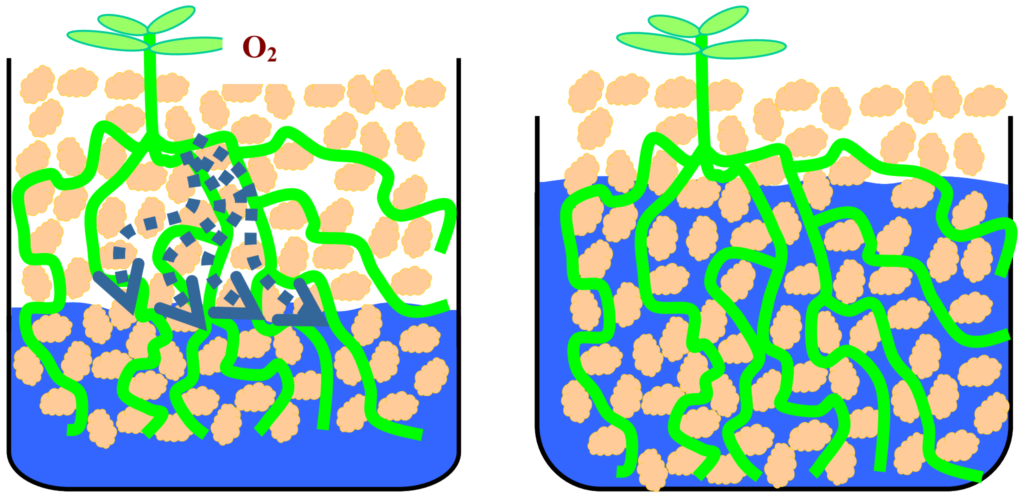
Some preliminary tests conducted prior to construction of the wetlands indicated that wastewater from the rest area had the following characteristics:

- BOD_5: 450 mg/L
- NH_3-N: 150 mg/L

- TSS: 180 mg/L

The hydrology of a conventional SFCW was judged as being inadequate to provide significant primary and secondary treatment to such high strength wastewater. Conventional SFCWs are constructed as a horizontal plug-flow reactor. The treatment in the wetland is accomplished by the microorganisms that come in contact with the wastewater. In the saturated substrate of the wetland, the microorganisms break down the pollutants. Treatment efficiency depends mainly on reduction in BOD_5, NH_3-N, and TSS. Microorganisms consume oxygen to break down organic carbon to carbon dioxide (CO_2), and BOD_5 is reduced. Microorganisms also reduce the NH_3-N level by a two-step process - nitrification and denitrification. Nitrogen is usually present in the form of nitrate, nitrite, and ammonia or ammonium ion, with the predominant form being nitrate. In the first step of the two-step processes, nitrification-ammonia and ammonium ions are transformed into nitrate. In the second step, denitrification-nitrate is converted to nitrogen (N_2) gas. So denitrificaion completes the nitrogen reduction/removal process. Nitrifying bacteria break up the pollutant in the presence of oxygen during nitrification. On the other hand, denitrification processes require an anoxic environment. Conventional wetlands have dissolved oxygen (DO) typically below 1.0 mg/L (US EPA, 2000; Behrends *et al*., 2001). This limited amount of oxygen can lead to a complete halt of nitrification. So nitrogen removal efficiency can be improved greatly by increasing the amount of oxygen present in the wetland substrate.

Research (Wieder *et al*., 1989) shows that there are three features that can be incorporated in a conventional SFCW to improve treatment performance. These are (1) the wetland may be divided into segments (as plug flow systems) that can operate and drain separately, (2) arrangements to allow step feeding the influent into the wetland, and (3) arrangements to allow for effluent recycling (Wieder *et al*., 1989). Scientists at the Tennessee Valley Authority (TVA) have developed a unique and patented SFCW system that is filled and drained alternatively at a frequency of two hours per cycle (Behrends *et al*., 2001). This technology (illustrated in Figure 3.12) has shown high ammonia removal for a variety of wastewater streams (Behrends *et al*., 2001). This fill and drain concept (US EPA, 2000) has been applied to a three-cell SFCW system in the village of Minoa, NY, and has shown some success in producing effluent quality that is better than the conventional plug flow SFCW systems (e.g. three cells in series). The Minoa system also has two cells in parallel and is operating at an alternating fill and draw mode followed by a third cell designed as a conventional plug flow reactor, similar to the design adopted at the Greenfield site.



Drain cycle Fill cycle
Figure 3.12 – Illustration of oxygen diffusion during fill and drain cycle

The fill and drain scheme has shown some success as it can increase the amount of oxygen in the wetland substrate - a key component for removal efficiency. During the drain cycle, oxygen from the air diffuses through the thin film of water surrounding the plant roots and the biofilm on the wetland substrates. During the fill cycle, plant roots and biofilms on the substrate are filled by the anoxic wastewater (Fig. 3.12), and the microorganisms get enough oxygen to break down the pollutants. Because of the large surface area present in the SFCW due to plant roots and substrates, the oxygenation of the rhizosphere and the substrate biofilms is substantial and rapid. This can potentially decrease the long HRT required for the nitrogen removal associated with the conventional SFCW systems.

Two parallel wetlands operating under the fill and drain scheme and one conventional polishing wetland cell are being used in the Greenfield rest area. It was expected that the modified design would reduce the effluent concentration to meet permit limits.

3.4 INSTRUMENTATION AT THE GREENFIELD SITE

Some of the objectives behind the construction of the Greenfield's wetland treatment system were to provide an understanding of the function of the constructed wetlands, quantify pollutant removal, and develop management strategies. So the treatment facility has been instrumented to collect data at various locations in the system. These collected data are being used to model the system and to assess its performance. The following sections provide a description of the instruments installed within the wetland system.

3.4.1 FLOW MEASUREMENT

The system has both open channel flow as well as pressurized flow. For open channel flow measurements, two types of flow meters are in place - three ultrasonic flow meters (see Figures 3.13 and 3.14) and a V-notch weir (Figure 3.15) are used at specific locations in the wetland system.

Figure 3.13 – Ultrasonic flow meter
(Source: http://www.environmental-expert.com/technology/greyline/level.htm)

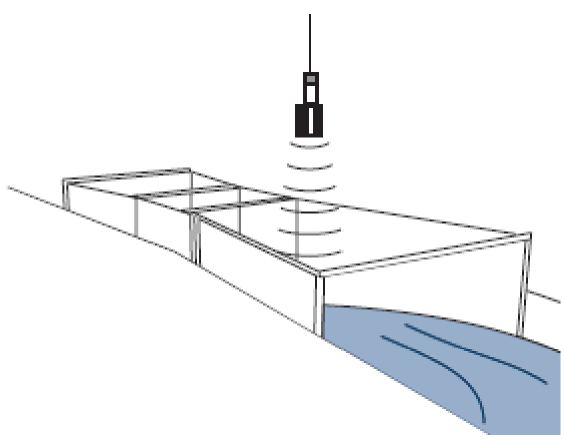


Figure 3.14 – Flow meter detecting the amount of flow in the open channel
(Source: http://www.greyline.com/pdf/SLT32.pdf)

A 22.5^o V-notch weir (F-1 in Fig. 3.3) is used along with an ultrasonic flow meter between the septic tanks (Figure 3.15). Both are used together to record the effluent flow rate from the first septic tank. This facility uses a Greyline OCF-IV flow meter. This non-contacting ultrasonic sensor is mounted above the liquid level. It has a user friendly calibration system and it is easy to set up the monitor to display measurements in specified units (ft, cm, gallons, liters, etc). Standard sensors can measure a depth of up to 32 ft. A picture of the V-notch weir is shown in Fig. 3.15 for illustration purposes. Two other flow meters (F-2 and F-3 in Fig. 3.3) are Palmer-Bowlus flumes equipped with ultrasonic level sensors. They are simple and effective flow measuring devices. Four inch size flumes are used on the site and are recommended for a flow range of 5-55 gpm. One flume, F-2, is located downstream from the parallel wetlands to measure the flow going to the third polishing wetland. The second flume F-3 is placed after the polishing wetland cell W-3.

Figure 3.15 – Flow over the V notch weir is being measured by the flow meter F-1

EMCO Unimag 4411e magnetic flow meter (Figure 3.16) is sued after the surge tank to measure the total inflow to the wetland system. Sparling FM657 magnetic flow meters (Figure 3.17) are being used after the dosing chambers to measure the flows. A magnetic flow meter is a volumetric flow meter that does not have any moving parts, and is ideal for wastewater application or any dirty liquid that is conductive or water-based.

Magnetic flow meters operate based on Faraday's law of induction (Figure 3.18). In electromagnetic measurement, the flowing medium corresponds to a moving conductor whose induced velocity is proportional to the flow velocity, and is detected by two measuring electrodes and then transmitted to an amplifier. Flow volume is computed on the basis of the pipe's diameter. The constant magnetic field is generated by a switched direct current of alternating polarity. The mag flow meters typically measure flow with velocity ranging from 0.01 to 10 m/s.

Figure 3.16 – EMCO Unimag 4411e magnetic flow meter
(Source: http://www.advancedflow.com/pdf/Data_Sheets/4411e_DS.pdf)

Figure 3.17 – Sparling FM657 magnetic flow meter
(Source: http://www.muellersales.com/pdf/spa_tigermag_fm657.pdf)

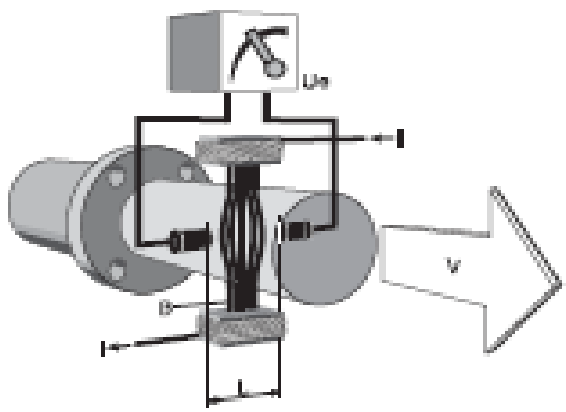


Figure 3.18 – Magmeter working principle
(source: http://www.ferret.com.au/Specsonline/files/212.pdf)

3.4.2 WATER QUALITY SAMPLING

To understand how well each component of the wetland system is working, four automatic samplers (see Figure 3.19) were installed to collect wastewater samples at various points in the system. These samplers are the 6712R refrigerated samplers by Teledyne Isco. The first sampler, AS-1 was installed before the septic tank, ST-2, to sample effluent from ST-1. The sampler AS-2 was placed after the second septic tank, while AS-3 is placed after the parallel wetlands on the recirculation branch. The fourth and the last sampler, AS-4 collects effluents from the third wetland cell. Their locations are schematically shown in Fig. 3.3.

Figure 3.19 – Water Quality Sampler
(Source: http://www.isco.com/products/products3.asp?PL=201202010)

The 6712FR refrigerated samplers are designed to withstand harsh indoor and outdoor environments. The cabinet of the refrigerator is corrosion proof, and molded from polyester resin fiberglass and supported by a stainless steel frame. A UV-resistant gel coating provides a smooth, non-porous finish for added protection and easy cleaning. The inside of the refrigerator is thick-foamed to provide insulation to preserve samples at EPA recommended 39^{o}F (4^{o}C). It also has built-in heater to automatically ensure that the samples will not freeze.

The sampler components are

(a) Controller

(b) Center section
(c) Peristaltic pump
(d) Liquid detector
(e) Strainer
(f) Suction line
(g) Stainless coupling
(h) Pump tube
(i) Bulkhead fitting
(j) Discharge tube
(k) Distributor arm and spring.

The controller in the sampler allows selecting between standard programming and extended programming mode. In standard programming mode, the controller allows a step by step sampling sequence. Extended programming mode can be used to choose more complex options including “smart sampling” notification triggered by any of up to 16 inputs. The strainer in the sampler prevents clogging of the suction side. Isco provides four different types of strainer to match application requirements.

When the sampler takes a sample, it draws liquid through the strainer that is connected to the pump tube by a suction line. The sample passes the liquid detector, which senses the liquid. From the detector, the sample follows the pump tube through the pump to the bulkhead fitting and through the discharge tube to the sample bottle. All four samplers used in the wetland system have a 24 bottle sampling kit.

A typical sampling cycle consists of
(1) The sampler moves the distributor arm over the bottle that is to receive the sample. The bottle number can be specified from the controller.
(2) The pump reverses for pre-sample purge.
(3) The pump direction changes, filling the suction line.
(4) When the detector senses liquid, the sampler begins measuring the sample.
(5) After depositing the sample, the pump again reverses for a post-sample purge.

Samples from the four locations have been collected on an intermittent basis since the wetland system has been in operation.

3.4.3 WEATHER STATION

A weather station was installed at the site to collect data on rainfall, wind speed, temperature, and evapotranspiration. These data are important to determine hydrologic balance within the wetland system. These data could also help to correlate reaction rates with weather data for different biological and chemical processes occurring in the system.

The wetland system uses the automated Campbell Scientific's ET106 (See Figure 3.20) which is an automated system. This is designed for commercial agriculture and irrigation scheduling. The station calculates potential evapotranspiration (ETo), which is the amount of water lost from the soil due to evaporation and plant transpiration.

Figure 3.20 – ET106 weather station
(Source: http://www.campbellsci.ca/Download/WeatherStations_Br.pdf)

The ET106 station consists of electronics housed in an environmental enclosure, a 2 or 3 meter aluminum mounting pole, and meteorological sensors. The station is powered with a 7 Ahr sealed-rechargeable battery that can be float-charged with AC power or a #10616 10-watt solar panel.

The enclosure includes electronics for measuring sensors, processing and sensoring data, and communicating with a central computer. Data can be telemetered via phone or short-haul models. The latter is used in the Greenfield wetland system. The ET106 is configured in minutes using Visual Weather software. Visual Weather software supports programming, manual or scheduled data retrieval, and report generation. The software also includes an on-board equation to calculate ETo based on the FAO-56 Penman Monteith equation, crop water needs, growing degree days, wetbulb temperature, dewpoint, wind chill, and chill hours. In the Greenfield wetland system, the ET106 is configured to give hourly data based on the Penman Monteith equation. Table 3.1 lists the measurement range and accuracy of the standard ET106 in measuring various hydrologic components.

Table 3.1 – Operating range and measurement accuracy of the weather station ET106

Hydrologic Component	Operating Range	Measurement Accuracy
Solar Radiation-Silicon photocell sensor		Absolute error in natural daylight is ± 5% maximum, ± 3% typical.
Rainfall-Tipping bucket rain gauge		± 1% accuracy at 2 inches per hour or less rainfall.
Wind Speed-Cup anemometer	0 to 49.5 m/s (0 to 110 mph)	± 0.11 m/s (± 0.25 mph) when <10.1 m/s (22.7 mph); ± 1.1 of true when >10.1 m/s (22.7 mph).
Wind Direction- Weather vane	360^o mechanical, 356^o electrical.	Accuracy $\pm 4^o$.
Relative humidity	0 to 98% RH.	± 3% for 0-90% RH, ± 5% for 90-98% RH.
Air temperature	-25 to 60^oC	$\pm 0.8^oC$ accuracy.

(Source: http://www.campbellsci.ca/Download/WeatherStations_Br.pdf)

3.5 DESCRIPTION OF THE DATA

Construction of the system started in the winter of 2002. Installations of all the instruments except the weather station were completed by February of 2004. The weather station was installed two months later in mid April. The data collection from the flow meters started in September 2003, a few months before the complete installation of instruments. From Dec 2003, drinking water data has been recorded. On Feb 10^{th}, 2004, data from the INDOT datalogger were collected for the first time. On the same day, wastewater samples from different locations of the wetland system were also collected. But, later that month, LS-3 and M-2 had operation problems and it was found that INDOT datalogger was not grounded. The problems were quickly resolved. However, during the last two years of operation of the system, all the instruments except the weather station were out of service from time to time. They were repaired and soon put back to the system. Table 3.2 provides a time line describing when some of the measurement devices were not functional during wetland operations. Availability of data from various instruments is summarized in Table 3.3. The summary is prepared on 10-day intervals. The “P” in the table indicates the data are partly available during those entire 10 days. Complete availability of the data in the table is indicated by “O”. A preliminary analysis of the data shows that some of the recorded values are not reasonable and are designated by “?”. The table also shows that the flowmeters have recorded daily flow values rather than hourly flow values during the first few months of operation. From Feb 2004, the flowmeters started collecting data on hourly basis.

Similarly, magmeters though programmed to record flow data every minute, have recorded the data every 3 to 5 minutes during the first year of operation. Unfortunately, most of the time, magnetic flow meter M-2 was out of service. Flow meter F-2 has not recorded any data during the entire year of 2005. So, although a large data set is available from the system’s operation, there are only few instances when all the instruments provided uninterrupted data. In the following paragraphs, the data are further described.

Table 3.2 - Wetlands equipment chronology

Date	Event
Feb. 3, 2004	Finished connecting magmeters M1 thru M4 to INDOT datalogger. Reset magmeter totalizers
Feb. 10, 2004	Site visit, collected data from INDOT datalogger and grab samples. Changed record interval to 1 Hr. on Greylines.
Feb. 23, 2004	LS3 shut down. INDOT datalogger found to be not grounded. M2 showed bad coils. Collected data from INDOT datalogger and Greylines. Reprogrammed magmeters and INDOT datalogger M1 Full Scale Output = 140GPM. Reset totalizer @ 2:46PM - was 3916 counts M2 Full Scale Output = 100GPM M3 Full Scale Output = 75 GPM M4 Full Scale Output = 200 GPM. Reset totalizer @ 2:51PM - was 3716 count
March 5, 2004	Grounded Telog datalogger. Collected trend and event data.
April 15, 2004	Installed weather station. Wind direction not accurate (+/- 10o). Collected flow data. Magmeter flow data diskette corrupted.
May 19, 2004	Site visit, collected data from INDOT datalogger, weather station & open channel flowmeters. Connected communication wires from weather station into water softener building. Noted that wetlands had been bypassed since March LS3 alarm was active and cell #3 was flooded.
June 7, 2004	Site visit, collected data from INDOT datalogger & open channel flowmeters. Installed CR10 on magmeters.
June 15, 2004	Site visit, collected data from CR10 on magmeters.
July 23, 2004	Site visit, collected data from CR10 on magmeters and F1, F2, F3, and weather station. Pulled monitor on F3 for repair.
Sept. 22, 2004	Site visit, reinstalled F3.
Oct. 21, 2004	Site visit, reinstalled M2.
Nov. 23, 2004	Site visit, collected data from CR10 on magmeters and F1,& F3, and weather station. Pulled monitor on F2 for repair. Pulled remote transmitter on M2 for repair.
Dec., 2005	Started the setup for SCADA system. Flow data collection was temporally unavailable.
July, 2006	Flow conditions and some other measurements were ready to be downloaded on the website.

Table 3.3 – Wetland data condition

2003	Jan			Feb			March			April			May			June			July			Aug			Sep			Oct			Nov			Dec		
	1	11	21	1	11	21	1	11	21	1	11	21	1	11	21	1	11	21	1	11	21	1	11	21	1	11	21	1	11	21	1	11	21	1	11	21
M1																																				
M2																																				
M3																																				
M4																																				
F1																											P	D	D	D	D	D	D	D	D	D
F2																											P	D	D	D	D	D	D	D	D	D
F3																											P	D	D	D	D	D	D	D	D	D
Drinking																																		O	O	O
Weather																																			P	P

2004	Jan			Feb			March			April			May			June			July			Aug			Sep			Oct			Nov			Dec		
	1	11	21	1	11	21	1	11	21	1	11	21	1	11	21	1	11	21	1	11	21	1	11	21	1	11	21	1	11	21	1	11	21	1	11	21
M1				P	3	3	P	3	P	?	?	?	P	5	5	P	P	P		P	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
M2				P	3	3	P	?	?	?	?	?	P	5	5	P	?	?												P	O	O	P			
M3				P	3	3	P	3	P	?	?	?	P	5	5	P	P	P		P	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
M4				P	3	3	P	3	P	?	?	?	P	5	5	P	P	P		P	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
F1	D	D	D	P	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
F2	D	D	D	P	O	O	O	O	O	?	?	?	O	O	O	O	O	O	O	O	P						P	O	O	O	O	O	P			
F3	D	D	D	P	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	P						P	O	O	O	O	O	P		P	O
Drinking	P					P	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
Weather	O	O	P								P	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O

2005	Jan			Feb			March			April			May			June			July			Aug			Sep			Oct			Nov			Dec		
	1	11	21	1	11	21	1	11	21	1	11	21	1	11	21	1	11	21	1	11	21	1	11	21	1	11	21	1	11	21	1	11	21	1	11	21
M1	O	P			P	O	O	P	P	O	O	O	O	P		P											P									
M2																											P					P	O	O	P	
M3	O	P			P	O	O	P	P	O	O	O	O	P		P											P					P	O	O	P	
M4	O	P			P	O	O	P	P	O	O	O	O	P		P											P					P	O	O	P	
F1	O	O	O	O	O	O	O	O	O	O	O	O	O	P													P	O	O	O	O	O	O	O	P	
F2																																				
F3	O	P						P	O	O	O	P																								
Drinking	O	O	O	O	O	O	O	P																												
Weather	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	P											P	O	O	O	O	O	O	O	P	

M1, M2, M3, M4: Minimum Unit in Minute O: Full Data Available P: Partial Data Available ?: Questionable Da
F1, F2, F3, Drink., Weather: Minimum Unit in Hour 3: 3-Min Interval 5: 5-Min Interval D: Daily Interval

3.5.1 FLOW METER DATA

Flow meter data from F-1 corresponds to wastewater inflow rate in to the wetland system. Available F-1 data were compared with drinking water data each month to confirm the accuracy of flow meter readings because wastewater is generated from the drinking water or tap water. These two data sets should show similar trends and should be strongly correlated to each other. The drinking water data includes usage from both the north and south rest areas. Care needs to be exercised as wastewater from both sides was not always directed to the wetland system.

The last drinking water and F-1 data set were recorded over a year ago (Table 3.3). Figure 3.21 shows drinking water and F-1 data recorded in June, September, and October-November of 2004. In September 2004 (Fig. 3.21b), the flow meter data exceeded the drinking water values by a large difference indicating that the data recorded by F-1 was inaccurate. But, during October-November, the F-1 data matched very well with the drinking water data (Fig. 3.21c). On other hand, the F-1 data in June of 2004 shows values that are about half the value of the drinking water data set (Fig. 3.21a).

During this time, the wetlands were receiving wastewater only from the north rest area. However, the wetlands had not received any wastewater for few days during this month (see flow rates of F-1 between day 12 to day 16 in Fig. 3.21a).

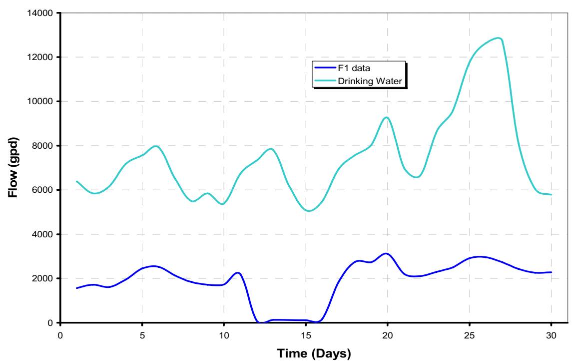


Figure 3.21(a) – Drinking water and F-1 recorded in June, 2004

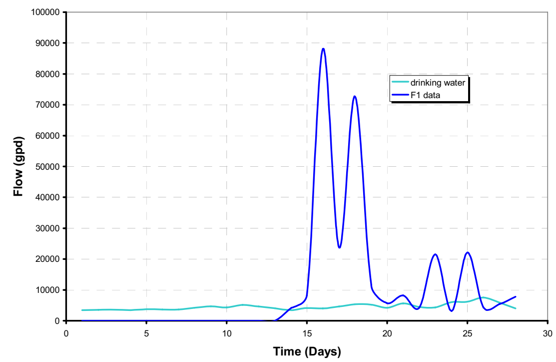


Figure 3.21(b) – Drinking water and F-1 recorded in September, 2004

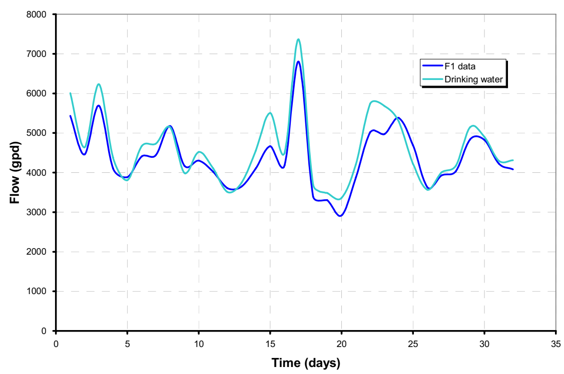


Figure 3.21(c) – Drinking water and F-1 recorded from Oct 22 to Nov 22, 2004

Data from the flow meters F-1, F-2, and F-3 were also compared to drinking water data, and some of these results are shown in Figure 3.22. Specifically, data from June and October 2004 are studied here. Since the inception of the flow meters, F-1 and F-2 data along with drinking water have been available without interruption during these periods. However, data from these flow meters are not always accurate. For instance, data recorded by F-2 exceed both F-1 data and drinking water data as shown in Fig. 3.22a. Indeed, on some days the discrepancy between F-2 data and drinking water data is more than 700 gallons per hour. The data do show some similar trends in that the peaks and troughs are fairly consistent in time. Similarly, F-2 data are very high in Oct. 2004 as seen in Fig. 3.22c, even though the timing of the peaks and troughs are again replicated.

Data from F-3 were not always consistent either. Fig. 3.22b is an example of F-3 data that does not track to drinking water data. For about eight days in October, 2004, F-3 data were reasonable but again rose to very high values (Fig. 3.22d). Flow meters, F-2 and F-3 are expected to have fairly large errors, especially for low flows, but these data indicate that F-2 and F-3 data need to be viewed carefully. F-1 data tend to be more reliable when compared to drinking water data because F-1 is a V-notch weir, while F-2 and F-3 are Palmer Bowlus flumes.

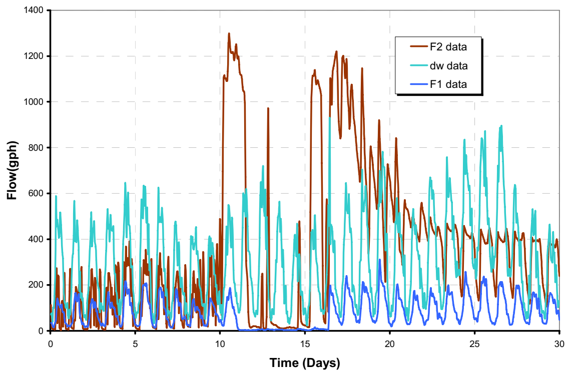


Figure 3.22(a) – Drinking water and recorded data from F-1 and F-2 in June, 2004

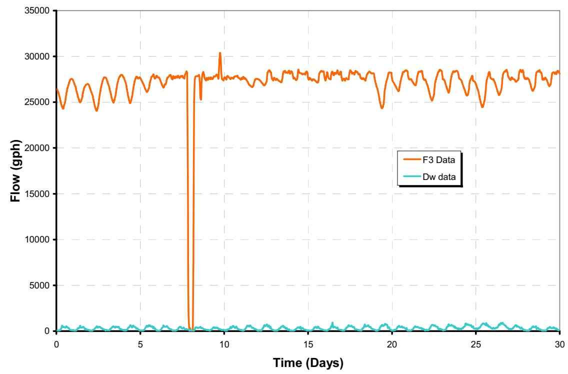


Figure 3.22(b) – Drinking water and F-3 recorded data in June, 2004

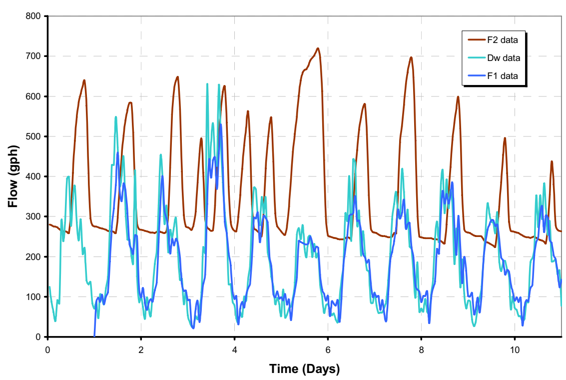


Figure 3.22(c) – Drinking water, F-1, and F-2 recorded data in last 11 days in Oct., 2004

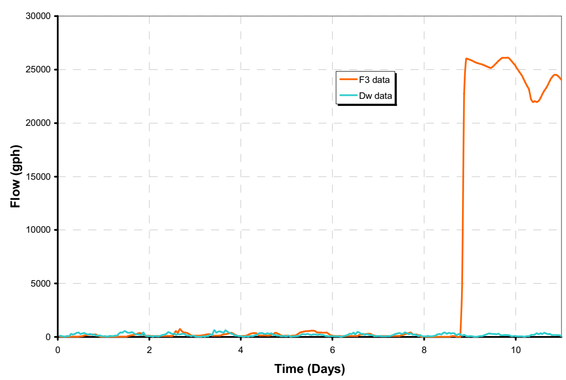


Figure 3.22(d) – Drinking water and F-3 recorded data in last 11 days in Oct, 2004

3.5.2 MAGNETIC FLOW METER DATA

Magmeters record the flow rates from the dosing tanks where the water flows under pressure. Since the operation of the wetland system, all the magmeters were simultaneously functional only during a short period from October 22nd to November 22nd, 2004. Magmeters M-1, M-2, and M-3 recorded data most of the time during 2004, while in 2005 these were in operation only for few months (see Table 3.2). Figure 3.23 shows some samples of magmeter readings, and needs to be interpreted in conjunction with

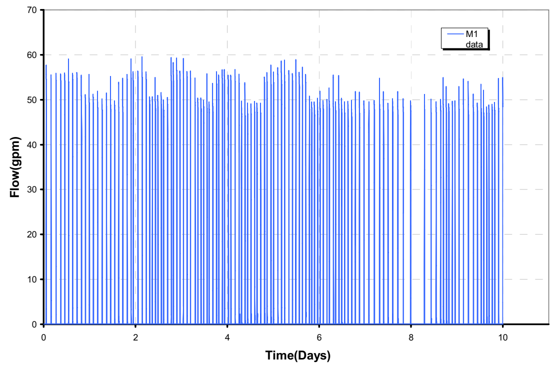


Figure 3.23(a) – M-1 recorded data in April 21 to 30, 2004

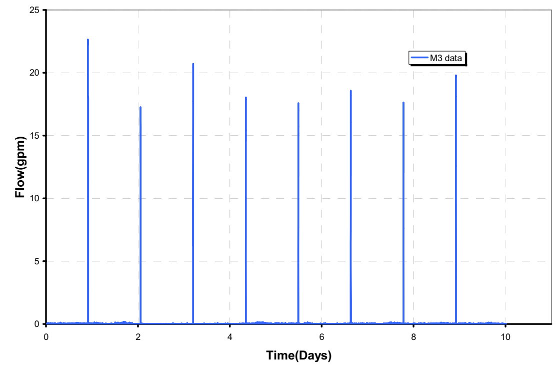


Figure 3.23(b): M-3 recorded data in April 21 to 30, 2004

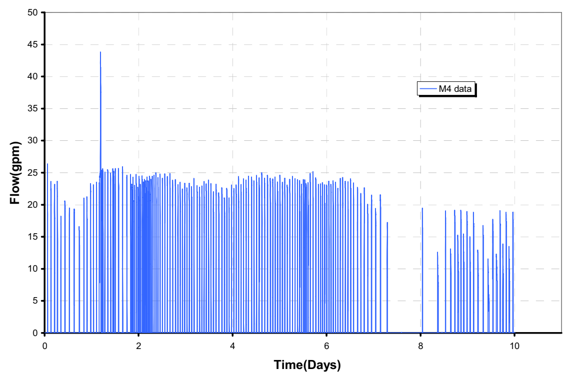


Figure 3.23(c) – M-4 recorded data in April 21 to 30, 2 004

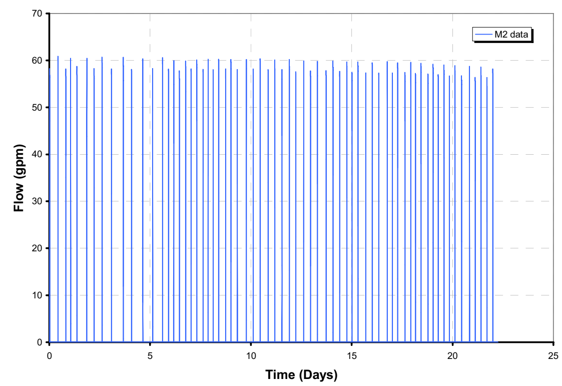


Figure 3.23(d) – M-2 recorded data in Nov 11 to Dec 16, 2005

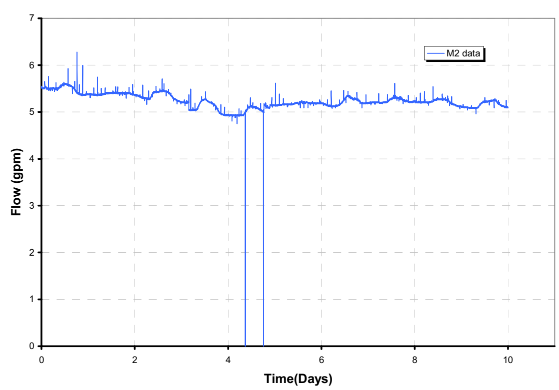


Figure 3.23(e) – M-2 recorded data in last 10 days in Oct., 2 004

Fig. 3.3. The magmeters are located immediately downstream of lift stations and reflect the magnitudes of flowrates and intermittency of the pumps. For instance, Fig. 3.23a shows data from M-1 for some days in April 2004. M-1 flow is dictated by pumping schedule of LS-1. The figure indicates the LS-1 pumps are operating a little over 50 gpm. Similarly, M-3 data in Fig. 3.23b indicate that LS-3 pumps are operating at about 18 gpm

in April of 2004. This data also indicates that the pumps in LS-3 switch on less frequently than LS-1. Fig. 3.22c shows a sample of M-4 data that indicates LS-4 is operating at 22 gpm on an average. The data recorded by the magmeters is not always consistent. For instance, M-2 data in Fig. 3.23d for a different time period indicates an average pumping rate of 60 gpm for LS-2. This is in contrast to the 5 gpm pumping rate shown in Fig. 3.23e. Given the high recycling rate, the data in Fig. 3.23d for M-2 would seem to be reasonable, as even a continuous pumping rate of 5 gpm in Fig. 3.23e from LS-2 cannot accommodate the recycle volume.

3.5.3 WEATHER STATION DATA

Data had been recorded continuously by the weather station since its installation until the first week of June, 2005. Sample of rainfall data in October, 2004, are shown in Fig. 3.24. Rainfall data is the primary component of the hydrologic budget that is produced by the weather station.

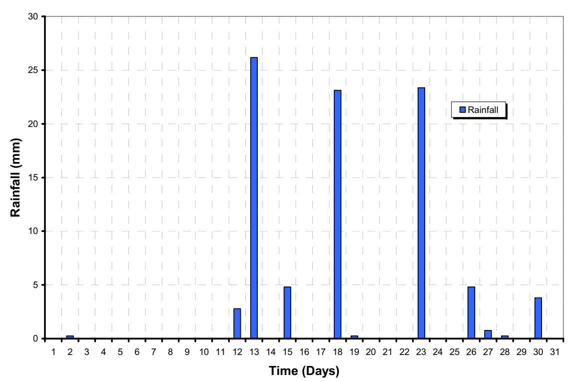


Figure 3.24 – Rainfall data recorded data in October, 2004

It would appear that the data have errors and inconsistencies that make interpretation more challenging.

CHAPTER 4

HYDROLOGIC PERFORMANCE

4.1 INTRODUCTION

As described in the previous chapter, the entire system includes a pair of wetlands with alternate fill and draw scheme along with recirculation. This makes the system rather complex for the estimation of hydraulic retention time (HRT) - which is commonly used as a wetland performance index. HRT estimation is made more difficult because of transient nature of the system with the water level and flowrates fluctuating over time. The model estimates the volume of water in the wetland cells by simulating the performance of the entire system, and computes how depths vary in the wetland cells during fill and drain cycles.

The hydraulic model of the Greenfield wetland system was built using a systems approach with the aid of Simulink in MATLAB. With the Simulink model editor, a block diagram representing the entire wetland system was created first. Model simulations were conducted for about 10 consecutive days starting from November 1st to November 10th, 2004. The model was then validated using a ten-day consecutive data set from October 2004. The model computations were based on one second time step. Subsequent sections in the chapter describe how each of the elements of the wetland complex was represented in the model. Topics covered in this chapter are validation using observations, and recognizing the limitations of the model. Details of the modeling effort are available in Sultana (2006).

4.2 MODEL DESCRIPTION

Each part of the wetland system was modeled to mimic its operation as closely as possible. Description of each component follows:

Septic Tanks: The two septic tanks are capsule-shaped containers. The maximum diameter of the tank is 8 feet, and the inlet and outlet pipes are 6 inches in diameter that are placed at a height of 7 feet from the bottom of the tank. Consequently, the tanks are always full to a height of 7 feet, and the wastewater effluent coming through the inlet pipe passes out of the tank by the outlet pipe after a small time lag. As in Fig. 3.22c, F-1 data was compared with drinking water data, and it was observed that the time series are nearly identical indicating a small time lag that is practically negligible. In the model, septic tanks are designed like a gate through which the wastewater flows out almost instantaneously towards the parallel wetlands.

***Lift Stations*:** The system has 4 lift stations (LS-1, LS-2, LS-3 and LS-4). The model includes all the four lift stations. LS-1, LS-2, LS-3 have a cross section of 8.5 feet by 5.5 feet with a full depth of 9 feet each. LS-4 has a circular cross section with diameter of 4 feet and a full depth of 9.5 feet. All the lift stations have two pumps each. During the completion of the wetland system, it was planned to run the pumps alternatively during slack hours in all the lift stations. But, because of increased usage of the rest area, both the pumps in LS-1 and LS-2 operated together to meet with the increased demand (see Fig. 3.24a and d). On the other hand, the observed data shows that the demands on LS-3 and LS-4 were relatively small, and so the two pumps in those two stations operate alternatively (see Fig. 3.24b and 3.24c). All the pumps stop pumping as the water depth falls to a height of 15 inches from bottom. In the model, LS-1 and LS-2 were modeled with two pumps operating together when the water depth rises to 39, and 45 inches respectively. The model was built to run with a single pump for LS-3 and LS-4 that operate when the water level rises to 50, 55 inches, respectively. Change of water level within the lift station was modeled by

$$\frac{dh}{dt} = \frac{Q(t)}{W \times L} \tag{4.1}$$

where, W is the width, and L is the length of the base area of the lift station, $Q(t)$ is the flow rate in the lift stations at time t, and $\frac{dh}{dt}$ is the change of water level within the lift station.

***Actuators*:** There are two actuator switches (ACT-1 and ACT-2) in the system. ACT-1 precedes the parallel wetlands and generates a signal to fill either of the parallel wetland cells, while ACT-2 is downstream of the two parallel wetland cells and controls emptying of the cells. This 'draw and fill' scheme operates on a time-based switch such that while W-1 is filling, W-2 is draining and vice versa. The switch occurs once a day from Tuesday to Friday, but twice a day from Saturday to Monday to accommodate the higher flow rates expected during weekends. In the model, both the actuators were modeled as a single element that sends a signal to alternate cells once daily from Tuesday to Friday and twice daily from Saturday to Monday to drain and fill alternatively.

***Wetland cells*:** The two parallel wetlands and the third polishing wetland work like large buckets. The parallel cells have a depth of 3 feet but are designed to have maximum water level of 2.75 feet to ensure subsurface flow. When the water level rises above the depth of 2.75 feet, wastewater overflows immediately through a pipe of 4 inches diameter regardless of the drain signal. On the other hand, when the wetland receives the drain signal from ACT-2 during the draining cycle, a valve opens up and the effluent is drained through another 4 inch diameter pipe. The wetlands are drained until the water level in the cells drop to 1.25 feet. Thus, a draining and an overflow mechanism have to be incorporated. This minimum depth of water in the cells is maintained to ensure plants survival between drain and fill cycles. However, the polishing wetland cell operates differently when compared to the parallel wetland cells. This wetland has a depth of 2 feet and is designed to have a constant water depth of 1.5 feet. Whenever the water depth rises above this threshold, water is instantaneously drained out from the wetland through a 6 inch diameter pipe. The wetlands not only receive wastewater but also rainfall that is added to the wetland cells directly regardless of whether the cells are filling or draining. In the model, each wetland cell is designed as a container of trapezoidal cross section. The parallel wetlands are filled during their filling cycle and drained during the drainage cycle. The water level change in the wetland cell is determined by the following equation

$$\frac{dh}{dt} = \frac{Q(t)}{(W + 6h(t))(L + 6h(t))\eta} \tag{4.2}$$

where, $Q(t)$ is the difference in inflow (Q_{in}) to and outflow (Q_{out}) from the wetland, $\frac{dh}{dt}$ is the change of depth within the wetland, W is the width of base, L is the length of the base of the wetland cell, and $h(t)$ is the depth of water at time t in the cell. The porosity, η, in equation (4.2) is used to reduce the volume of the wetland to effective volume. For the parallel wetlands, Q_{in} is effluent flow rate from LS-1 along with rainfall rate, and Q_{out} is the overflow and draining rate through overflow and drain pipes connected with the wetlands. Similarly, Q_{in} in the polishing wetland is the rainfall rate added with the small percentage of flow directed from the parallel wetlands. When the water level in the parallel wetland rises above 2.75 feet, then the excess water is drained out through a overflow pipe. Similarly, the excess water rising above 1.5 feet is drained out from the polishing wetland. The parallel wetlands are also drained through a drain pipe in response to a time-based switch. The quantity Q_{out} for overflow was modeled as:

$$Q_{out} = C_{dout1} A_{dout1} \sqrt{2g(h - h_{\max})}\,, \quad \text{for} \quad h > h_{\max} \qquad (4.3)$$

whereas, Q_{out} for draining was modeled as:

$$Q_{out} = C_{dout2} A_{dout2} \sqrt{2g(h - h_{\min})}\,, \quad \text{for} \quad h_{\min} \le h \le h_{\max} \qquad (4.4)$$

where, C_{dout1}, C_{dout2} are discharge coefficients, A_{dout1} and A_{dout2} are outlet pipe areas of the overflow pipes and draining pipes, respectively, and g is gravitational acceleration. The discharge coefficients are introduced to account for the effects of all energy losses including friction losses in the pipes and within the wetland cells along with all other minor losses. $h_{\max}$ in equation (4.3) was taken equal to 2.75 feet for parallel wetlands and 1.5 feet for polishing wetland. $h_{\min}$ in equation (4.4) was taken equal to 1.25 feet.

The third wetland cell is modeled as a horizontal flow reactor. The water level in the cell is maintained at a constant height of 1.5 feet. Response to overflow is instantaneous and effluent flows out through a 6-inch diameter pipe.

4.3 MODEL CALIBRATION

The model was calibrated using the consecutive 10-day data starting from 1st to 10th November, 2004, recorded by different instruments within the wetland system. The inflows to the entire system are F-1 data at the V-notch weir and rainfall data from the weather station (Figure 4.1). Evapotranspiration data were not included at this stage as outflow from the entire wetland complex as it was found small compared to rainfall intensities (see Figure 4.2). Note that the scales of y axis of the two graphs (Figs. 4.2a and 4.2b) are different.

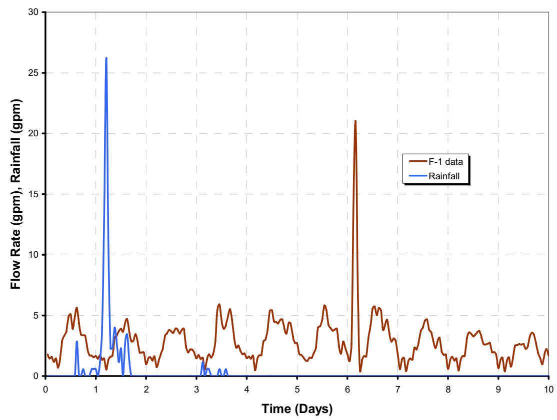


Figure 4.1 – F-1 data and Rainfall during November 1 to 10, 2004

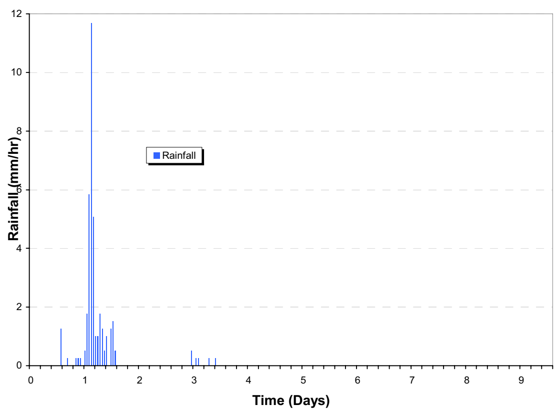


Figure 4.2(a) – Rainfall during the first 10 days of November, 2004

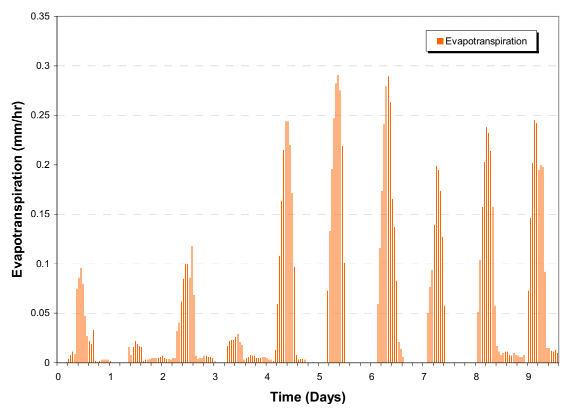


Figure 4.2(b) – Evapotranspiration during the first 10 days of November, 2004

The lift stations LS-1, LS-2 were modeled to have flow rates of 50 gallon per minute. These are shown in Figures 4.3a and 4.3b. LS-3 and LS-4 were modeled to have a flow rate of 15, 25 gallon per minute respectively (See Figs. 4.3c and 4.4d). Although the observations from M-2 show that the pump is pumping constantly at an average rate of 5.25 gallon per minute, this value was not used in the simulation because it was determined that the M-2 flow data were erroneous (see discussion in Section 3.5). After the wastewater flows out of the parallel wetlands, we note that 83 percent of the outflow is recycled back to the parallel wetlands while the remainder of the 17 percent was directed towards the third wetland cell, which was then compared with the F-2 data (Figure 4.4a). Since, the F-2 data also had problems with magnitude of flow, the model parameters were calibrated by matching the time to peak with the F-2 data set. The discharge coefficients C_{dout1} and C_{dout2} for the overflow and drain pipes in the parallel

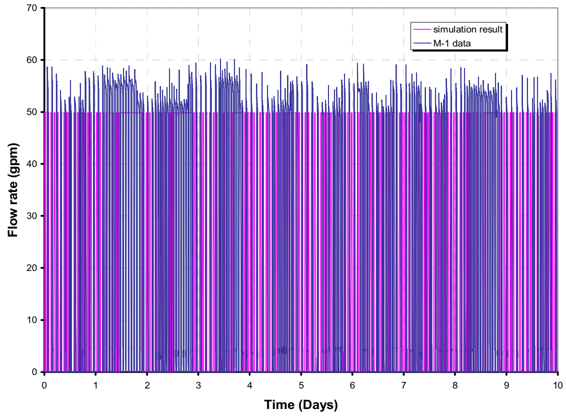


Figure 4.3(a) – M-1 data compared with simulation results

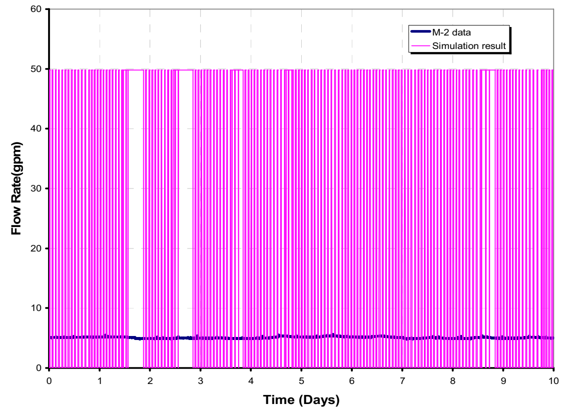


Figure 4.3(b) – M-2 data compared with simulation results

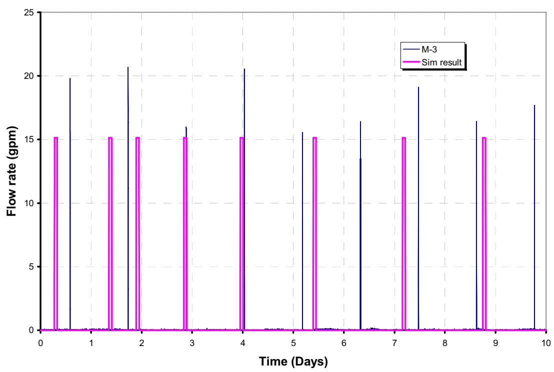


Figure 4.3(c) – M-3 data compared with simulation results

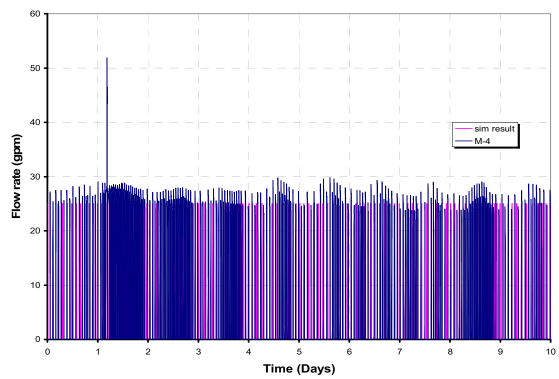


Figure 4.3(d) – M-4 data compared with simulation results

wetland cells were selected as 0.6 and 0.04, respectively by calibration using F-2 data as seen in Fig. 4.4a. The justification for this small value of C_{dout2} of drain pipe is because of the flow through the porous media as well as the drain valve in the drain pipe that opens up during the drain cycle. The observed peaks (in Fig. 4.4a) are due to the overflow rates and the troughs are due to the draining of the parallel wetland cells.

Similarly, the outflow from the third wetland cell was compared with the F-3 data (Fig. 4.4b) and C_{dout} for the overflow pipe in W-3 was chosen as 0.04. For LS-3, the time of pumping also depends on the fraction of the effluent from W-3 flowing to the biofield which was not known. So, in simulations, 17 percent of the effluent was directed towards the biofield while the rest flowed to the Greenfield's municipal treatment plant.

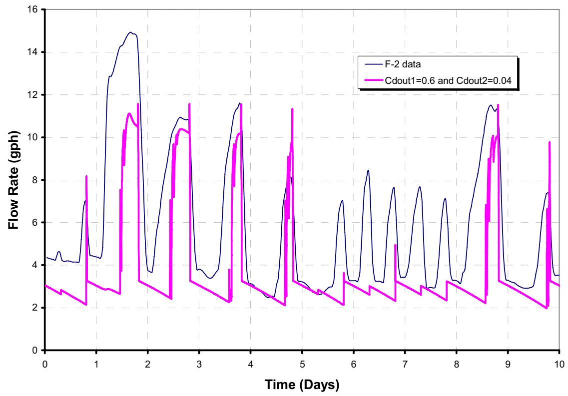


Figure 4.4(a) – F-2 data compared with simulation results ($C_{dout1} = 0.6$, $C_{dout2} = 0.04$)

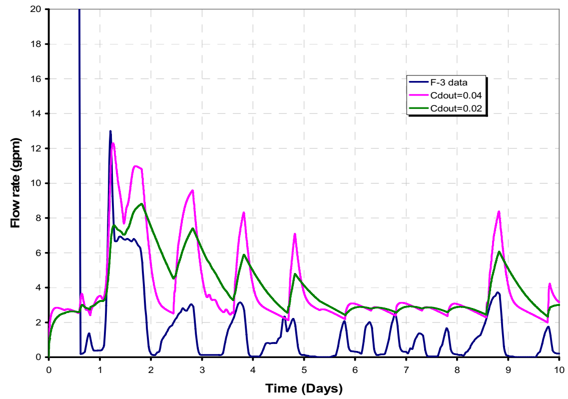


Figure 4.4(b) – F-3 data compared with simulation results ($C_{dout} = 0.02$,and 0.04). A value of 0.04 was chosen for C_{dout} from wetland cell W-3.

Sensitivity Analysis

Given some of the discrepancy with F-2 data, a sensitivity analysis was conducted to calibrate the model parameters. In the sensitivity analysis, values of each of the parameters (C_{dour1} , C_{dour2} , C_{dour}) were varied by lowering or raising their magnitudes (ranging between 0.2 to 0.8). The sensitivity of the model was qualitatively compared by graphing model output from each run with F-2 data set. It was observed that the model output is sensitive to the initial water level of the lift stations (Fig. 4.5c), and timing of drain signal (Figs. 4.5a and 4.5b). During operation, the parallel wetlands were known to receive drain signals once at 7:30 am from Tuesday to Friday, while at 7:30 am and 7:30 pm from Saturday to Monday. As mentioned earlier, Fig. 4.4a shows comparison of model results with F-2 data without any adjustment of this time. Almost all the observed peaks were estimated by the model except for the peaks during day 7 and 8. To analyze why the peaks on those two days could not be predicted, the time to drain/fill was varied. Figure 4.5 shows the model result when the drain/fill signal was activated approximately 3 (Fig. 4.5a) and 2 hours (Fig. 4.5b) earlier. This time shift was applied only over the duration indicated by the arrows in Figs. 4.5a and 4.5b. Two of the peaks model simulated (as shown in Fig. 4.4a) on day 7 and 10 were missed by the model (see Figs. 4.5a and 4.5b) with a change in time of drain/fill signal. However, the peaks on day 9 were maintained for a longer duration in Figs. 4.5a and 4.5b as compared to Fig. 4.4a. Comparing Figs. 4.4a, 4.5a and 4.5b it can be seen that the timing of the switching operation causes the magnitudes and timing of the peaks to change. Therefore, there might be a possibility that the wetland complex was not drained/filled everyday exactly at

7:30 am or 7:30 pm and on some days the complex might have had approximately 2 hours time delay of activating the drain/fill signals. Thus, it is necessary to know the exact time of fill/drain signal for accurate calibration of the model.

Fig. 4.5c shows the effect of initial water level in the lift station LS-3. With an initial depth of 4 feet, the timing of pumping by LS-3 estimated by the model closely matches with the timing of pumping recorded data by magmeter M-3. In Fig. 4.4d, M-3 data were compared with model results for different fractional amounts being diverted to the biofield as the exact amount towards the biofield was unknown. The model would seem to indicate that about 25 percent of wastewater from W-3 flows towards the biofield. At this percentage inflow towards biofield, the M-3 data shows that the pump is working 9 times within the 10 days period in November and the pump in the model is pumping 8 times within the same period.

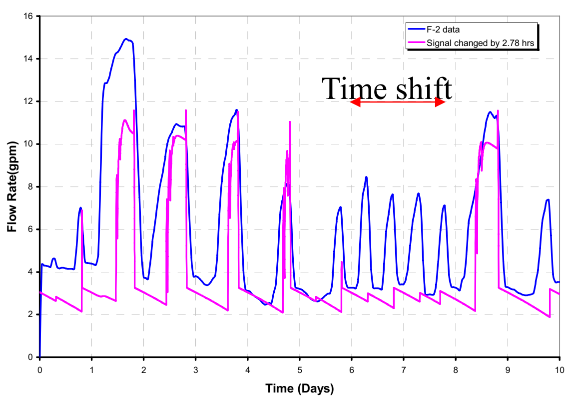


Figure 4.5(a) – Simulation result with the first drain signal 2.78 hours earlier

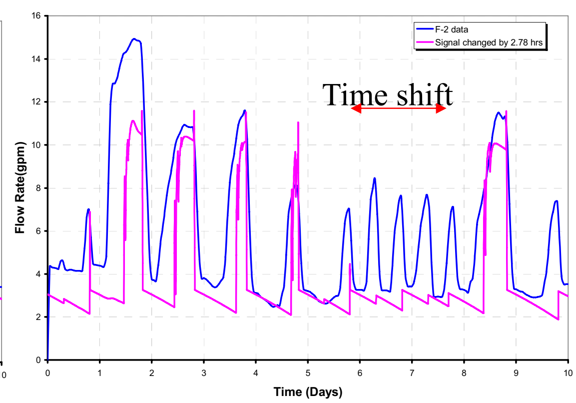


Figure 4.5(b) – Simulation result with the one of the drain signal about 1.94 hours earlier

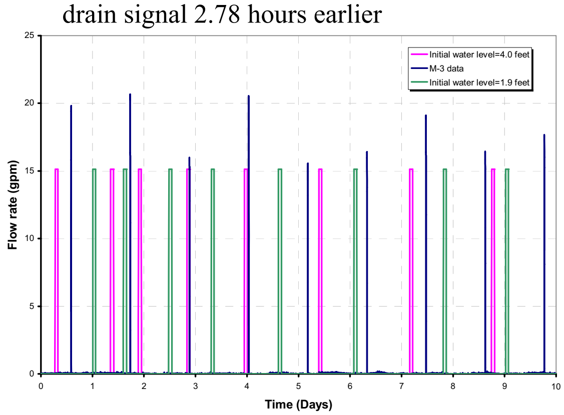


Figure 4.5(c) – Simulation results with different initial water level in the LS-3

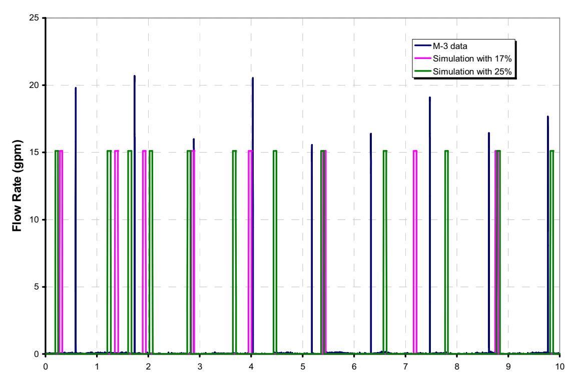


Figure 4.5(d) – Simulation results with different percentage of wastewater diverted towards the biofield

Model Results

Figure 4.6 shows the volume change in the wetlands as estimated by the model. There is an increase in volume of water in the parallel wetlands after day 1 (Fig. 4.6a) caused by the rainfall event observed during day 2 (see Fig. 4.1). The volume of water started to decrease on the third day but again increases for a low intensity rainfall at the end of 3rd day. By the end of 4th day, the effect of the rainfall diminishes and volume of water in the parallel wetlands almost reaches a constant value of 6500 cubic feet for the following 2 days (Fig. 4.6a). Then on the 7th day, another increase in volume is observed due to the large inflow recorded by flow meter F-1. Although, there was no peak observed in drinking water data during this period when it was compared with the F-1 data, the F-1 recorded data was not corrected. The effect of this increased flow rate lasted for the following two days. Subsequently, the volume of water again reaches a constant value of 6300 cubic feet. On the other hand, the volume of water in W-3 is almost constant (see Fig. 4.6b). There were small increases in volume estimated by the model on 2nd, 3rd, 4th, 5th, and 9th days. Two peaks were noted on the second day. The first one is due to the rainfall on the second day and the second peak is due to the fill/drain signal initiated by the actuator. The days when the parallel wetlands are filled/drained twice per day, there is no peak observed. But, on days with single fill/drain cycle an increase in volume of water in W-3 is indicated by the small peaks (Fig. 4.6b). This is because during single fill/drain cycle per day, the wetland cells get more time to fill in with or drain out with wastewater than during two fill/drain cycle per day (see Figure 4.7a).

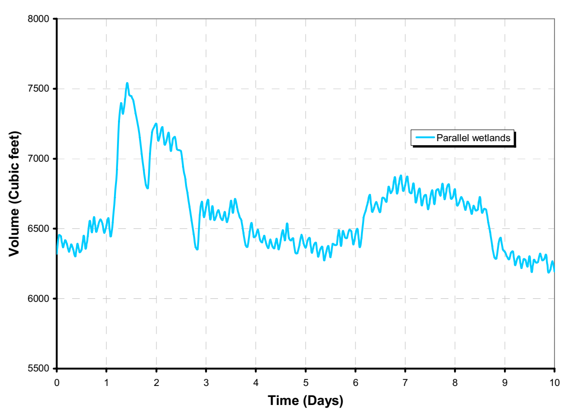


Figure 4.6(a) – Estimated volume change by the model within both the parallel wetland cells W-1 and W-2

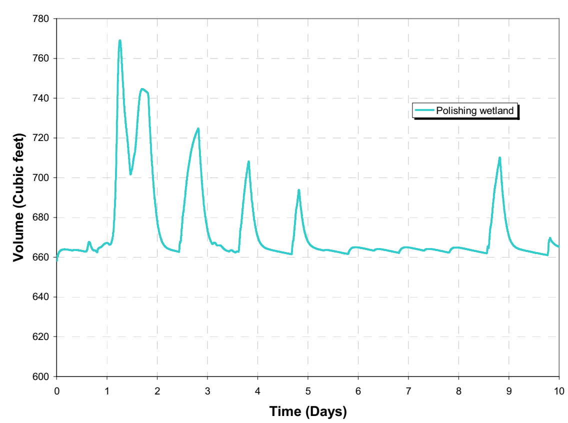


Figure 4.6(b) – Estimated volume change by the model within the polishing wetland cell W-3

The model calculated the depth change in the wetlands based on inflows and outflows.

When observing depths in W-1 and W-2 individually, the results show that when cell 1 is draining, cell 2 is filling and vice versa (Fig. 4.7a). Between the 1st day (which is Monday), there was drain/fill signal twice and in the following 4 days, there was drain/fill signal only once per day. On the 6th, 7th, and 8th day, two drain signal are observed again. Fig. 4.7b also shows the depth change in the third wetland W-3 that reflects the volume change results in Fig. 4.6b. The increase in depth because of inflow from the flow splitter is transmitted rapidly by the overflow pipe.

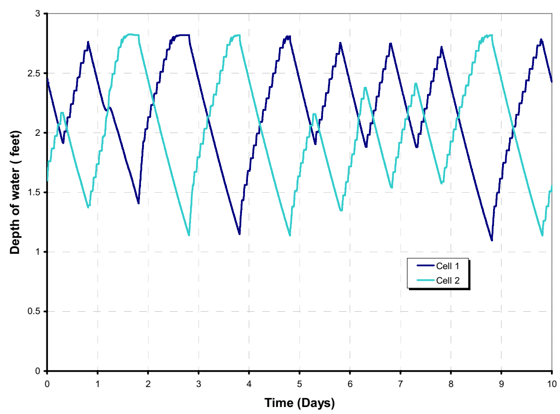


Figure 4.7(a) – Estimated depth change by the model within the parallel wetland cells in W-1 and W-2

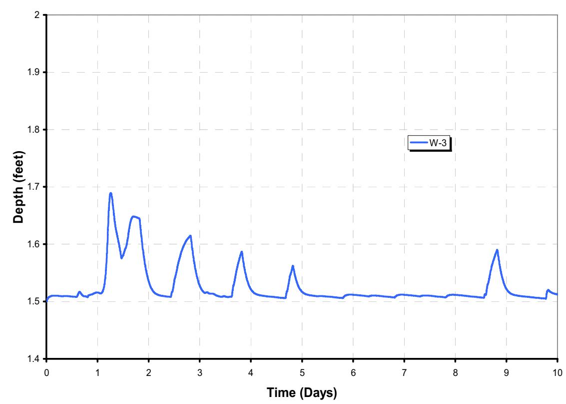


Figure 4.7(b) – Estimated depth change by the model within the polishing wetland cell W-3

The volume calculated by the model was used to measure volumetric efficiency of the wetlands which is one of the important hydraulic performance metrics. The volumetric efficiency was calculated using the equation:

$$Eff(t) = \frac{1}{\eta \widehat{V}_A t} \int_0^t \eta \widehat{V}(t) dt \tag{4.5}$$

where $Eff(t)$ is the volumetric efficiency at time t, η is the porosity, $\widehat{V}(t)$ is the volume of wastewater in the wetland at time t, and $\widehat{V}_A$ is the available wetland volume. The volumetric efficiency varies with time initially, but becomes almost constant when the transients die out. The long term efficiency for parallel wetlands is about 0.67, and a slightly higher efficiency of 0.70 for the polishing wetland (Figure 4.8) is noted by the model. Another important wetland performance index is Hydraulic retention time (HRT) that is calculated for the parallel and polishing wetlands using the volume estimated by the model. These values are shown in Table 4.1. Although volumetric efficiency of the polishing wetland is higher than the parallel wetlands, its low HRT is indicative of its low treatment efficiency.

Table 4.1 – Estimated HRT and volumetric efficiencies of the wetland cells during Nov 1 to Nov 10, 2004

Wetlands	**HRT**	*Volumetric efficiency*
Parallel wetlands W-1 and W-2	10.78 days (combined cells)	0.67
Polishing wetland W-3	1.1 days	0.7

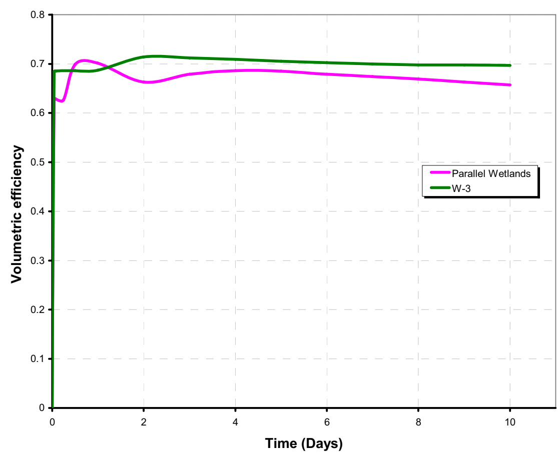


Figure 4.8 – Estimated volumetric efficiency of the wetlands

4.4 MODEL VALIDATION

The model's output was validated by comparing data from 10 consecutive days from October 22nd to October 31st, 2004. Figure 4.9 shows the input information (F-1 data and recorded rainfall) for those 10 days period. Recorded readings by different instruments are compared with model outputs (see Figure 4.10).

F-2 recorded data were problematic and the model was calibrated earlier only to follow the trend of the F-2 data sets (see discussion in Section 3.3). During the last 10 days of October, 2004 the model output that also followed the trend of F-2 data (Fig. 4.10a). The peaks occurred at about the same time as indicated by the data recorded by F-2. The troughs generated by the model were about 2 gpm below the troughs of the recorded data, and the patterns are similar.

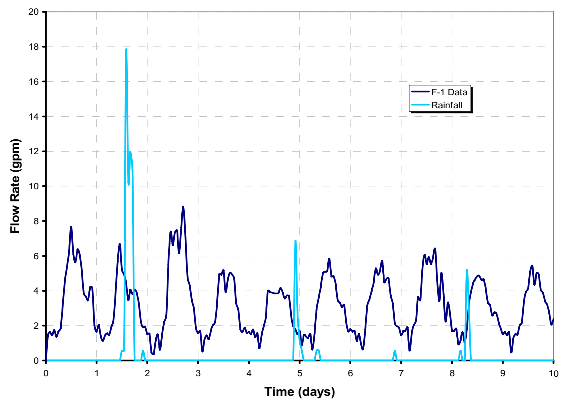


Figure 4.9 – F-1 data and Rainfall from October 22 to 31, 2004

Fig. 4.10b shows the model output from the lift station LS-1 that was modeled to pump at 50 gpm. The output is validated by comparing the model result with magmeter M-1 readings during this period. The model output matched fairly well with the M-1 data set.

However, model output from the second lift station did not match with the magmeter M-2 recorded data (Fig. 4.10c). Data recorded by M-2 were again found to be inaccurate and similar discrepancy persists as in the calibration results (discussed in Section 3.3).

In Fig. 4.10d, model output from LS-3 was compared with the data recorded by M-3. Results show that the timing of the pumping in the model and in the recorded data agrees very well. During those 10 days of October, 2004, the pump in LS-3 pumped 8 times whereas observed data from M-3 shows that the pump was switched on one more time.

In the model, the 4th lift station LS-4 was modeled to pump at 25 gpm and model output matched well with the observed data from magmeter M-4 during the 10 days period in Oct. of 2004 (Fig. 4.10e).

Model output of flow towards the third wetland cell W-3 was compared with the F-2 recorded data (see Fig. 4.10f) and the output matched well with observed data for the first seven days. But, from the eighth day the observed data were found to be very high which is indicative of inaccurate recording by F-3 (see discussion in Section 3.3).

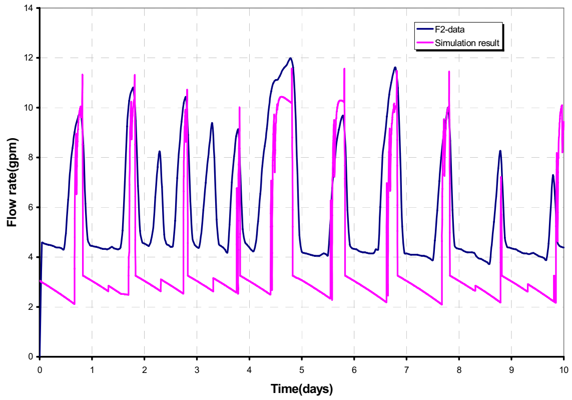


Figure 4.10(a) – F-2 data compared with simulation result

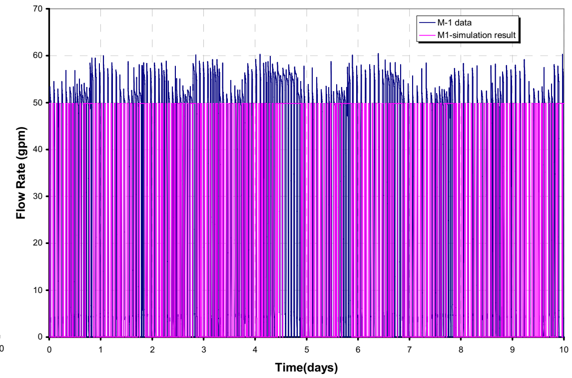


Figure 4.10(b) – M-1 data compared with simulation result

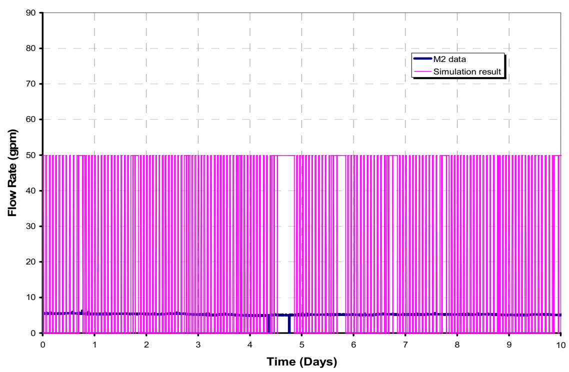


Figure 4.10(c) – M-2 data compared with simulation result

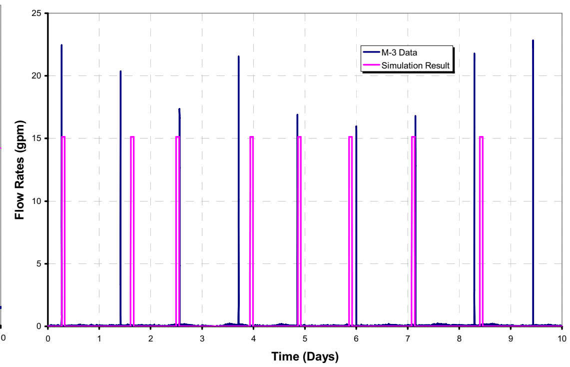


Figure 4.10(d) – M-3 data compared with simulation result

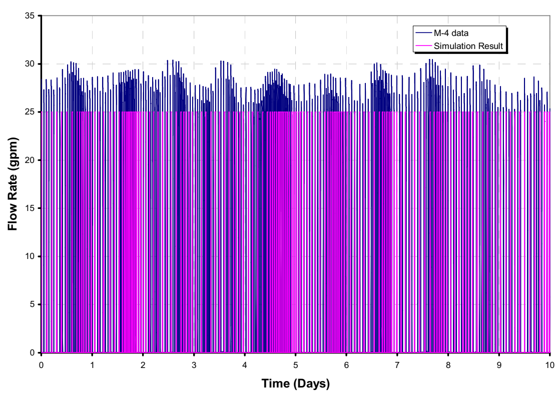


Figure 4.10(e) – M-4 data compared with simulation result

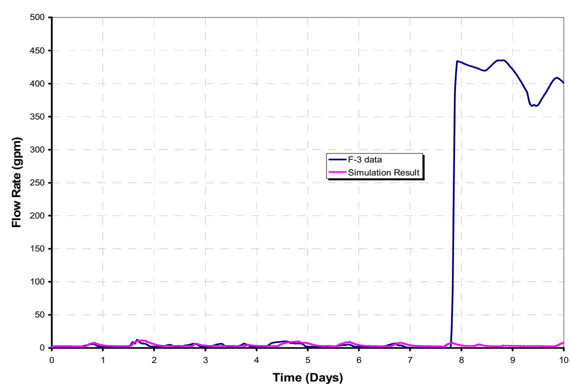


Figure 4.10(f) – F-3 data compared with simulation result

Figure 4.11a shows model estimation of the change in volume of water in the parallel wetlands W-1, and W-2. The sudden rise of volume of water in day 2 is due to the rainfall event observed during day 2 (Fig. 4.1). This rainfall event is followed by 3 more rainfall events on days 5, 7, and 9. But, the duration and intensity of these rainfall events were much smaller compared to the rainfall on day 2. As a result, the effect of the first rainfall lasted for the next 3 days but the effects of the latter rainfall events were smaller, and the increases in model estimates of volumes of water in W-1, W-2 were less. Similarly, the volume of water estimated in W-3 by the model shows an increase due to the rainfall events and inflows during the period (see the peaks in Fig. 4.11b).

The model estimates the change of depth of water in the parallel wetlands (are shown in Figure 4.12a). It can be seen from the figure that when cell 1 is filling, cell 2 is draining and vice versa. There are fill/drain signals from the actuator during the 2nd, 3rd, 4th days which were Saturday, Sunday, and Monday. Again on the 9th and 10th day (Saturday and

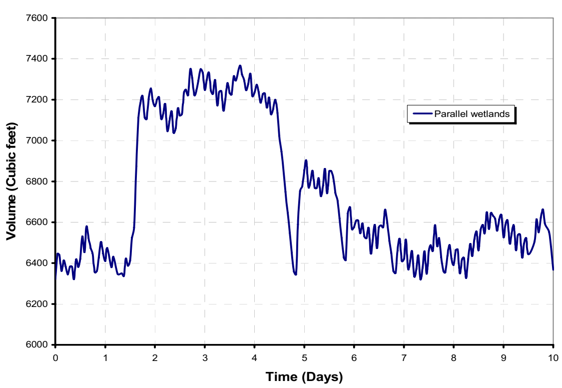


Figure 4.11(a) – Model estimation of change of volume in both the parallel wetlands

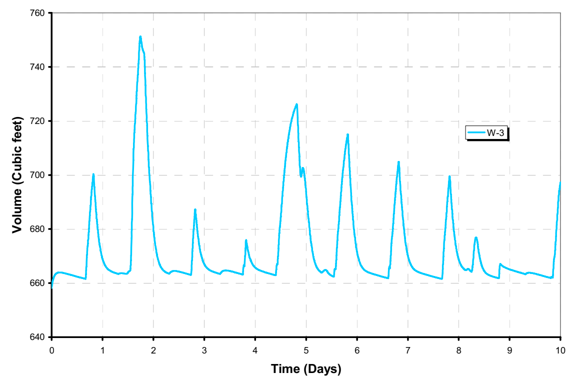


Figure 4.11(b) – Model estimation of change of volume in W-3

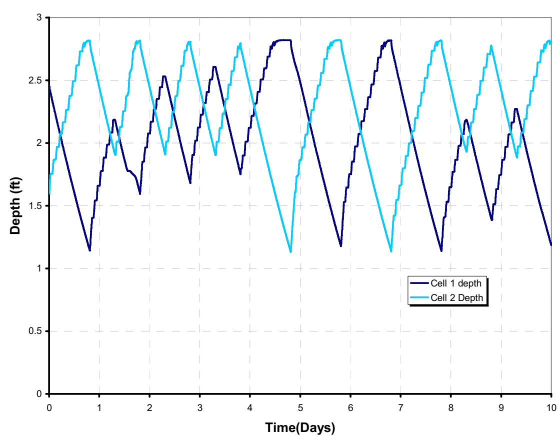


Figure 4.12(a) – Model estimation of change of depth within the parallel wetlands

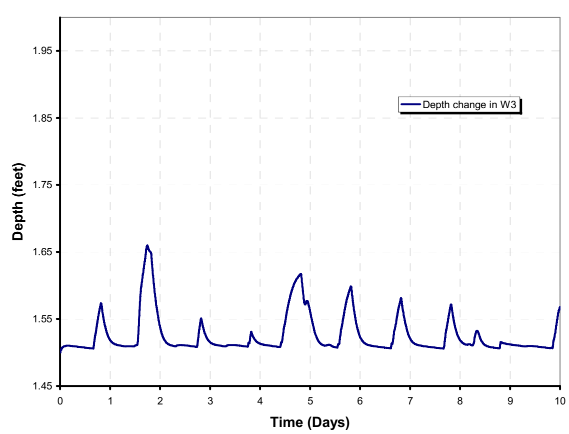


Figure 4.12(b) – Model estimation of change of depth within the polishing wetlands

Sunday, respectively), the drain signal was sent twice. The change of depth of water in W-3 estimated by the model during this period (Fig. 4.12b) show the depth was almost constant at 1.5 feet. The peak observed on day 2 is larger than the other peaks because of the high intensity rainfall on day 2.

Efficiency of the parallel wetlands and polishing wetlands during these 10 days are calculated as 0.65 and 0.69, respectively (Figure 4.13), and close to the calibration results.

4.5 LIMITATIONS OF THE HYDROLOGIC MODEL

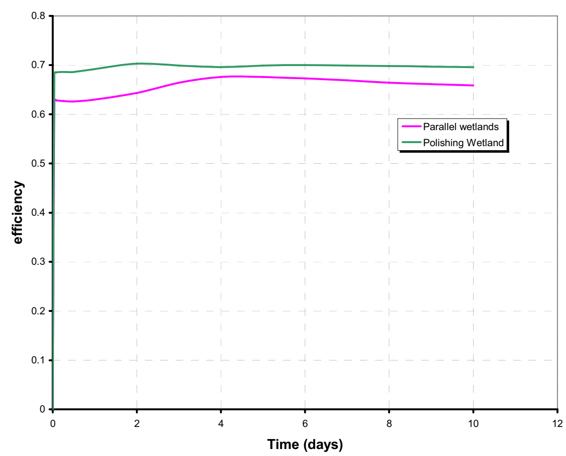


Figure 4.13 – Volumetric efficiency in the wetlands during last 10 days in Oct, 2004

The model parameters were calibrated using the data recorded by different instruments installed within the wetland. But, the available flow meter F-2, F-3, and M-3 data sets showed inconsistent readings, and so some of the model parameters calibrated may not be accurate. For these reasons, the model could not be validated in a rigorous manner.

Each of the components in the wetland system was modeled as a lumped unit in an approximate fashion. The internal mechanisms of each element were not considered. The effect of short circuiting, or dead zones observed in the wetlands were not considered.

For the wetland system, a simplified hydrologic budget as in US EPA (1988) was used in equation (2.6). In the wetland system, the potential evapotranspiration (ET_0) has been recorded by the weather station. The station estimate of ET_0 is based on Penman-Monteith equation that uses the effects of radiation, humidity, temperature, and wind speed measured in real time. But, actual evapotranspiration is affected by many other factors such as type of vegetation, development stage of the vegetation, and type of soil and its cover (FAO UN, 1988). Typically, for a vegetated wetland, actual evapotranspiration is approximately 30 percent of the ET_0 during non growing season but about 120 percent of the ET_0 during the growing season (~ 3 months). Based on the preliminary data, a substantial amount of water loss is not expected by ET_0 even during the summer season as it was offset easily by rainfall events (see Fig. 4.2). So, the model includes only rainfall and wastewater data as inputs to the wetland system.

The wetlands are reported to have ponding for some periods. However, those periods were not recorded. Model results using the November and October data show no ponding in the wetlands.

Conclusions on efficiency and HRT should be viewed as reasonable estimates at this time. With the availability of future data, more confidence can be developed in the model results.

CHAPTER 5

EXPERIMENTAL METHODS

5.1 KEY ANALYSIS OBJECTIVES

The environmental treatment capabilities of the wetland system were measured in terms of Biochemical Oxygen Demand (BOD_5), Total Suspended Solids (TSS), and Ammonia-Nitrogen (NH_3-N) concentrations. These parameters of the wastewater were tested because they have been accepted as standard methods, have been used in many previous studies, and are used by governing bodies as measures of the quality of treated waste streams.

5.2 DATA COLLECTION

Field samples were collected in disinfected 1000 ml plastic bottles provided by ISCO. Samples were obtained on a monthly basis from each automated sampler (AS-1 through AS-4, see Fig. 3.3 for locations) as well as form the biofield and surge tank. Samples were sealed in individual bottles and kept in a sealed bucket until analysis at the Purdue University Laboratory for waste characteristics. If laboratory analysis had to be postponed, samples were refrigerated to maintain acceptable temperature, and were isolated from laboratory contaminants. Samples were normally analyzed within 6 hours of collection. In a worst case scenario, some samples were analyzed within 48 hours of collection. The analysis protocol was adopted earlier by Dr. James E. Alleman and N. Shah, and was continued by T. Konopka.

5.3 STANDARD ANALYSIS PROCEDURES

Quantities and concentrations of contaminants present in the wastewater samples collected at the rest area were analyzed according to the standard procedures and calculations presented in the Standard Methods for the Examination of Water and Wastewater (17th ed.). BOD_5 concentrations were determined according to procedure 5210 B. 5-Day BOD Test. Seed used for oxidizing biodegradable organic matter in samples was obtained from the West Lafayette Wastewater Treatment Plant. Nitrogen concentrations were determined according to procedure 4500-NH_3 F. Ammonia-Selective Electrode Method. This method measures nitrogen in the form of ammonia, where dissolved ammonia (aqueous NH_3 and NH_4^+) is converted to aqueous NH_3 by raising pH of the sample to above 11 with a strong base. Total suspended solids were determined according to procedure 2540 D. Total Suspended Solids Dried at 103-105ºC.

5.4 QUALITY ASSURANCE AND QUALITY CONTROL

Quality Assurance measures were implemented during the procedures used throughout sampling and analysis in order to produce accurate and precise results. These measures helped in preventing bias, minimizing random error, and eliminating systematic error. Quality Control measures were taken to help produce accurate and precise results through the daily functions carried out during the collection and analysis of samples. Proper cleaning of sampling equipment and bottles, calibration of testing instruments, and analysis of blanks, replicates, and spikes helped ensure the quality of laboratory procedures.

The Purdue University environmental laboratory manager, Changhe Xiao, provided laboratory training, and he was also available to help ensure laboratory quality control standards. All chemicals and reagents used in the laboratory were analytical grade or better, and stored away from direct sunlight. Stock chemicals and reagents were always transferred to a clean container prior to weighing. After each use, glassware, plastic ware, or other laboratory equipment was washed with detergent, thoroughly rinsed with water, and finally rinsed with DI water. After drying, all equipment was stored in a dry cabinet. The laboratory where samples were analyzed was kept clean and organized. The room temperature was kept as constant as possible, and air quality was maintained as best as possible. Standard operating procedures reflecting university laboratory regulations were followed for all laboratory procedures.

5.4.1 BIOCHEMICAL OXYGEN DEMAND

Dissolved oxygen (DO) was measured using an YSI DO-meter, model 55. Calibration and maintenance of the DO Meter was performed according to the manufacturer's specified procedures. The probe membrane was replaced as necessary, usually after the analysis of 3 lots of wastewater samples.

Aeration of dilution (DI) water in a plastic container was accomplished through supplying organic-free filtered shop air to the container. DI water was stored in light shielded containers, sealed with a loose container lid to allow a free exchange of air without contamination. Nutrients for the DI water were prepared in the laboratory and equilibrated to 20.5ºC when in use and sealed when not in use. Seeded DI water blanks were used as a check on the quality of seeded DI water. The DO uptake of seeded DI water in 5 days was checked to be between 0.6-1.0 mg/L. The quality of the unseeded DI water was checked by making BOD_5 measurements on a standard solution of 150 mg glucose/l and 150 mg glutamic acid/l. The 5-day BOD measurement of a 2% dilution of the glucose-glutamic acid standard solution was checked to be around 198 mg/L.

All samples were well mixed before transferring to BOD bottles and were equilibrated to the appropriate temperature if they were cooled before use. It was ensured that no air bubbles were present in the BOD bottles before incubation. Round glass stoppers were used along with water seals on bottles to guarantee an adequate seal and to prevent drying. All BOD bottles were appropriately labeled. All BOD bottles containing desired dilutions, seeded dilution water blanks, and glucose-glutamic acid checks were incubated at 20.5ºC for 5 days in a dark storage area. BOD bottles were also rotated to hold different samples after each sample lot analysis.

5.4.2 AMMONIA ION SELECTIVE ELECTRODE METHOD

The selective electrode method works on the principal of diffusion of gases across a permeable membrane. The electrode detects ammonia and the electrode potential (mV) as it diffuses through a hydrophobic gas-permeable membrane and reaches partial pressure equilibrium on both sides of the membrane. The amount of ammonia that passes through the membrane is proportional to the concentration of ammonia in solution.

For the ammonia selective electrode laboratory procedure, an Orion Ammonia Electrode model 95-12 was utilized. Calibration and maintenance of the electrode was performed according to the manufacturer's specified procedures. When not in use, the electrode was stored according to manufacturer's guidelines. The probe membrane was replaced as necessary, usually after the analysis of 3 lots of wastewater samples. Interferences (caused by volatile amines) in electrode readings were occasionally observed. Interferences may increase the charge on the electrode membrane, which may cause a high measurement. If readings during the preparation of the standard curve were not within an expected range (i.e. readings were extremely high), or if the slope of the standard curve did not appear normal, it was assumed that interferences had affected the membrane, which required the replacement of the membrane.

Samples were warmed to room temperature before analysis if they were refrigerated. The temperature of standards and samples remained consistent during calibration and testing. Samples and standards were stirred slowly with an insulated magnetic stirrer so that air bubbles were not sucked into solution and allowed to form on the membrane. 1 mL of 10 N NaOH was added to all standards and samples to increase pH to 11; this was done only after the electrode was immersed in the solution to prevent the loss of ammonia gas. The electrode was allowed to stabilize before recording mV values. The electrode was rinsed between each standard and sample with ammonia-free water. Ammonia-free water was prepared by adding 1 mL concentrated sulfuric acid or chlorine to distilled water, which was then protected from atmospheric contamination. Stock ammonium chloride solution was purchased commercially, while standard ammonium chloride solution was prepared in the laboratory.

A calibration curve on a logarithmic scale was generated by measuring the electrode potential for different concentrations of a standard solution of NH_4Cl (1, 10, 100 and 1000 ppm as N). While taking the readings, a pH adjusting solution of methanol and sodium hydroxide was added to maintain high pH during the reaction. Using the calibration curve, unknown concentrations of ammonia in the samples were determined. Analysis of spiked samples was used to determine the accuracy, or bias, of the analysis. The amount of spike was usually twice the concentration of the sample being analyzed.

To generate the calibration curve, the linear regression function on a computer spreadsheet was utilized. The use of this standardized statistical procedure produced consistent equations for the "best-fit" line, eliminating the guesswork or bias with a hand-drawn line. Calibration curves were checked for accuracy by using the calibration equation to convert the instrument response for the calibration standards into respective concentrations based on the established calibration curve. Reasonable agreement between the “true”, laboratory-prepared concentrations and the calculated concentrations from the calibration curve were ensured. Calculated concentrations were within 5 - 10% of the “true” concentrations.

5.4.3 TOTAL SUSPENDED SOLIDS

In order to get accurate results, 3 replicates of each sample (from each sampling point) were analyzed. Whatman filter papers, number 934-AH, were used for the procedure. In determining total suspended solids, samples were dried at 105ºC. Filters are dried in an oven at 105ºC for at least 1 hour. After drying, filters were stored in a cool and dry area until use. In measuring weights, the balance used was always zeroed before weighing filters. Samples were well mixed and unrepresentative particles were avoided when measuring volumes. Samples were filtered under vacuum, after which filters were washed with 3 successive portions of distilled water. Filters with samples were then dried, and cooled before weighing. Some samples were dried overnight on occasion to check drying efficiency.

CHAPTER 6

WETLAND PLANTS

6.1 IMPORTANCE OF WETLAND PLANT MEDIA

Constructed wetlands, similar to naturally occurring wetlands, are outfitted with one or more types of wetland plants, in combination with a rock or soil media in which they grow. The plant media within a wetland cell provides a variety of important functions that contribute to the well-being of the system and to wastewater treatment capabilities. Wetland plants sprout roots within the wetland which serve two main functions. Roots provide a surface for beneficial bacteria to grow on, allowing for the consumption and transformation of pollutants present in the influent waste stream. Roots also foster greater oxygen transfer from the atmosphere throughout the wetland. Oxygen within the system promotes adequate nitrification, which directly affects the treatment of ammonia. Plants within a wetland also consume water, thus removing it through transpiration. In a constructed wetland system, water transpiration through plants along with evaporation decreases effluent production. Evapotranspiration rates will vary depending on plant species and density, but rates from 1.5 to 2 times the pan evaporation rate have been reported in the literature (US EPA, 2000). Wetland plants also play a role in winter performance of constructed wetlands by reducing the heat-loss effects of wind and by insulating the wetland from cold temperatures. Aside from their chemical, physical, and biological benefits, wetland plants have the intrinsic value of being aesthetically pleasing. Typical wetland plants found in constructed wetland systems include *Carex lacustris*, *Scirpus acutus*, *Typha latifolia*.

6.2 LITERATURE REVIEW

A study performed relating effect of ammonia concentration to biomass production of five common wetland plants in a subsurface wetland application concludes that species with greater biomass could remove more nutrient ammonia from influent wastewaters than those with less biomass (Hill *et al.*, 1997). Monocultures of *Juncus roemerianis*, *Sagittaria latifolia*, *Phragmites australis*, *Scirpus acutus,* and *Typha latifolia* were studied under average concentrations of influent NH_3-N ranging from 20.5 mg/L to 82.4 mg/L. Significant differences in dry matter production were noticed. Under the testing conditions, dry matter production of *Juncus reomerianis* is at an extreme variance with no explanation, and the species shows extreme stress as little or no growth occurred. Of the remaining species, *Phragmites australis* has the greatest dry weight (17.4 g/m^2) and is not affected by ammonia concentrations. *Typha latifolia* and *Scirpus acutus* produce relatively similar dry weights of 11.5 and 10.5 g/m^2 respectively. *Scirpus acutus* dry matter production is maximized in the 30-50 mg/L of NH_3-N. *Sagittaria latifolia* is not affected by NH_3 concentrations but produces the least amount of dry matter with 8.8 g/m^2. The conclusion of the study is that harvesting a species with greater biomass could remove more nutrients on a per area and time basis (Hill *et al.*, 1997).

Another study found seasonal variation in COD removal in *Carex rostrata*, *Scirpus acutus*, *Typha latifolia* and an unvegetated control (Stein and Hook, 2005). Cold and warm seasons were simulated with temperatures of 4ºC and 24ºC, respectively. Results of the study show *Carex rostrata* to have improved removal of COD at 4ºC versus 24ºC. *Scirpus acutus* also shows improved removal of COD at colder temperatures versus warmer, but removal is slightly worse with the *Carex rostrata* monoculture. Sulfate reduction is limited by organic carbon availability at 24ºC, but is especially strongly reduced in cold temperatures. *Typha latifolia* shows decreased removal of COD at 4ºC versus 24ºC. Sulfate reduction is also limited by organic carbon availability at 24ºC, and reduction is even lower at cold temperatures. *Typha latifolia* has poor redox potential year-round. An unvegetated microcosm has the poorest removal of COD and sulfates and has the poorest redox potential. At 4ºC, COD removal is best with *Carex rostrata*, followed by *Scirpus acutus*, *Typha latifolia*, and the unplanted control (Stein and Hook, 2005).

Anaerobic microbial metabolism is generally favored during active plant growth at warm temperatures, when most oxygen is believed to be consumed within the root. Aerobic microbial respiration is at times favored during dormancy at cold temperatures, when root respiration is lower and more oxygen is available to microbes in the root zone (Stein and Hook, 2005). *Scirpus acutus* and *Carex rostrata* are most capable of increasing root-zone oxygenation during periods of plant dormancy at low temperatures, and this increase is believe to be sufficient enough to modify the overall chemistry of a wetland (Stein and Hook, 2005).

Different plant species' capacities to oxidize the root zone causes them to respond differently to seasonal cycles of growth and dormancy. Species' effects on wastewater treatment are most pronounced in winter. Physiological response of some plant species to seasonal dormancy and lower temperature (4ºC) permits increased oxygen transfer to the root zone of subsurface flow wetlands. The potential for plants to enhance aerobic treatment processes is more limited during periods of active plant growth and higher temperatures (24ºC). Warmer temperatures enhance removal at low COD concentrations but reduce removal at high concentrations (Stein and Hook, 2005).

Generally, temperature is a poor predictor of seasonal performance. However, effects of plants on seasonal performance patterns can be explained by seasonal variation in root-zone oxidation. The effects of plants on performance are frequently greatest during the coldest periods (dormancy) (Stein and Hook, 2005). Plant species selection may be more important to cold-season than to warm-season performance.

Planted constructed wetland systems as compared to unplanted systems show enhanced nitrogen and phosphorus removal, but only small improvements in disinfection, BOD, COD and TSS removal (Tanner, 2001). Research was carried out under hydraulic loading rates of 25-182 mm/day of domestic and agricultural wastewaters with varying levels of preceding treatment, and 8 different plant species. Sizes of pilot scale systems varied from 18-400 m^2 and experimental microcosm studies from 0.08-6 m^2. In the studies, BOD or COD removal capabilities were nearly unchanged in planted or unplanted systems. However, for paired systems, BOD concentrations are reduced by 2-5 g/m^3 for planted beds. TSS removal was also very similar for planted and unplanted systems. Planted wetlands showed a clear trend of improved total nitrogen removal. Enhanced phosphorus and metal mass removal was also observed as compared to unplanted systems. Planted beds showed small but consistent improvements in inactivation rates of fecal coliform and a range of other bacterial indicators as well as lower effluent concentrations of viruses than unplanted systems (Tanner, 2001). Comparison with unplanted controls after ~2 years of operation showed 1.6-6 times greater organic matter accumulation in the presence of plants. Accumulated organic matter provides additional sorption sites, sources of complexing and biochemically active substances, and substrates for microbial processes. This intensifies nutrient cycling, elevating the residence time of nutrients relative to that of wastewaters passing through them (Tanner, 2001).

Nitrogen and phosphorus removal capabilities of *Scirpus validus*, *Carex lacustris*, *Phalaris arundinacea*, and *Typha latifolia*, a mixture of the four, and an unvegetated control were greatly varied (Fraser *et al.*, 2004). These plants are fast-growing, tall stature, "clonal-dominants", that establish quickly and process a lot of energy (Fraser *et al.*, 2004). Testing was done during the second growing season, since research has shown that in constructed systems, more than one year me be needed to reach "natural wetland conditions" (Sistani *et al.*, 1996). Concentrations of applied nitrogen and phosphorus, high/low levels at 112/26.5 mg/L and 62/15.5 mg/L, respectively, were applied. Under these conditions, *Scirpus validus* was most effective in nitrogen and phosphorus reduction and high levels of nutrient input. *Carex lacustris* showed high effectiveness in removal capabilities at high inputs of nitrogen and phosphorus (similar to *Scirpus validus*), but also had the greatest dry biomass production at both high and low nutrient levels. *Phalaris arundinacae* was the least effective in nitrogen and phosphorus reduction, with treatment capabilities similar to unvegetated microcosms. *Typha latifolia* was the slowest to establish of the plants used in the study, and at high nutrient levels, growth was stunted or the plants were killed. Performance of the 4-species mixture was comparable to the removal capabilities of the *Typha latifolia* monoculture. For this species, removal capability at low nutrient levels was good, but removal capability at high nutrient level was average at best. Unplanted controls consistently had significantly higher nitrogen values than any vegetated microcosms (Fraser *et al.*, 2004).

Overall, *Carex lacustris* and *Scirpus validus* monocultures showed the best (and similar) performance. *Typha latifolia* and the 4-species mix, showed similar results, have significantly worse removal capabilities at high nutrient input than *Carex lacustris* and *Scirpus validus* monocultures. Unvegetated microcosms and *Phalaris arundinacae* monocultures had similar performance results; removal capabilities of both were the worst of this study (Fraser *et al.*, 2004).

Vegetated microcosms are shown to be more effective at reducing concentrations of total nitrogen and phosphorus from soil lechate than unvegetated microcosms. There is a differential species effect on the potential to reduce nitrogen and phosphorus. Plant mixtures are not necessarily more effective than monocultures at reducing nitrogen and phosphorus (Fraser *et al.*, 2004).

Riley *et al.* (2005) tested ammonium and COD removal capabilities of *Typha latifolia*, *Carex rostrata*, and an unvegetated control under constant influent levels of NH_3-N (40 mg/L) as the nitrogen source and COD (225 mg/L) as the organic carbon source. The year-long study included seasonal changes created by adjusting the temperature of the environment of the microcosms to 24ºC, 14ºC, and 4ºC in the summer, fall/spring, and winter, respectively. Conclusions of the study showed that *Carex rostrata* had superior year-round organic carbon removal and increased root-zone oxygenation over *Typha latifolia* and the unplanted control. Ammonium removal was greater in winter than in the summer in the presence of COD in a *Carex rostrata* monoculture. Ammonium removal by a *Typha latifolia* monoculture was not affected by season, but half as much COD was removed in the summer season as was removed in the winter season when compared to *Carex rostrata*. The unplanted monoculture performed the worst in all categories (Riley *et al.*, 2005).

6.3 RATIONALE

It is first important to note that COD (Chemical Oxygen Demand) and BOD (Biological Oxygen Demand) tests are similar in that, either chemically or biologically, both tests oxidize organic carbon in wastewater and measure the relative oxygen-depletion effect of a waste contaminant. Both have been widely adopted as a measure of pollution effect. The BOD test measures the oxygen demand of biodegradable pollutants whereas the COD test measures the oxygen demand of biodegradable pollutants plus the oxygen demand of non-biodegradable pollutants that can be oxidized. To measure oxygen demand, BOD relies on bacteria to oxidize readily available organic matter during an incubation period. COD uses strong chemicals to oxidize organic matter. Thus, the studies performed by Riley *et al.* (2005), Stein and Hook (2005), and Tanner (2001) are relevant and applicable in that their measurements of COD relate to BOD measurements taken at the Greenfield wetland site.

There is a growing body of evidence that some wetland species, including *Carex rostrata*, can enhance the oxygen available for microbial processes in winter over summer (Riley *et al.*, 2005). Plant-mediated oxygen transfer affects water treatment most in winter and, as such, the choice of plants is potentially more important to subsurface flow wetland performance during the winter than during the growing season (Stein and Hook, 2005). Strong differences between species were apparent during cold temperatures and plant dormancy but are minimal at warmer temperatures when plants were actively growing (Stein and Hook, 2005). The efficiency of aerobic respiration over anaerobic respiration is so great that only a modest shift toward aerobic conditions could obscure or even reverse the effect of temperature on microbial activity. Thus, moderate increases in oxygen availability in winter could offset effects of cold temperatures (Stein and Hook, 2005).

Increased rates of BOD removal and ammonia oxidation from wastewaters and elevated dissolved oxygen concentrations have been recorded in the root-zone of wetland plants (Dunbabin *et al.*, 1988). Root oxygen release was credited for improved rates of NH_3-N removal by stimulating nitrification (Tanner, 2001). Plants primarily affect treatment performance through ecosystem engineering, enhancing key nutrient transformation processes (e.g. nitrification and denitrification) by root-zone oxygen release and supply of organic matter (Tanner, 2001). For *Scirpus* species grown in wastewater dilutions, Tanner (2001) found that increasing BOD rather than nutrients was the primary environmental factor influencing the depth of root penetration. Also, reduced winter nitrogen removal was attributed to decreased plant uptake during the dormant season and dramatically decreased microbial metabolism at colder temperatures (Kadlec and Knight, 1996).

Results of the studies overlap and coincide with each other with regard to plant species and treatment effectiveness. *Typha latifolia* was least effective, possibly due to its shallow rooting zone and the inability to create an effective environment for various microbial communities (Gersberg *et al.*, 1986). Also, Coleman *et al.* (2001) showed that there was no significant difference between *Typha latifolia* monocultures and mixed systems. *Carex lacustris*, one of the best performers of one study, was noted to have the greatest amount of biomass of the tested species (Fraser *et al.*, 2004). An increase in biomass, both living and dead, was found to enhance rates of denitrification and have improved removal efficiencies of nitrogen.

6.4 CONCLUSIONS DRAWN FROM LITERATURE

Unvegetated controls in all the studies consistently showed the same results; they all had poorest removal capabilities in all aspects of wastewater treatment. Planted systems showed enhanced nitrogen and phosphorus removal and improvements in disinfection, BOD, COD and TSS removal (Tanner, 2001). Thus, plants are shown to be valuable to the treatment processes that occur within a subsurface constructed wetland.

Typha latifolia is an attractive species for a constructed wetland application because it has been shown to produce more biomass than *Scirpus acutus* and *Sagittaria latifolia* (Hill *et al.*, 1997). However, *Scirpus acutus* produced only slightly more biomass than *Typha latifolia*, making it nearly as desirable. Although *Typha latifolia* was not effected by high NH_3 concentrations (Hill *et al.*, 1997) or by temperature (Riley *et al.*, 2005), this species showed decreased removal of COD at cold temperatures as compared to warm temperatures, and poor year-round redox potential (Stein and Hook, 2005). *Carex rostrata* and *Scirpus acutus* showed improved removal of COD at cold temperatures as compared to warm temperatures (Hill *et al.*, 1997). *Carex rostrata* had superior year-round organic carbon removal and increased root-zone oxidation over *Typha latifolia* as well as greater ammonium nitrogen removal in the winter than in the summer in the presence of COD (Riley *et al.*, 2005). However, *Scirpus validus* was most effective in nitrogen and phosphorus reduction (Fraser *et al.*, 2004). *Carex lacustris* had great dry biomass production with very effective removal of nitrogen and phosphorus as well. *Typha latifolia*, on the other hand, was slowest to establish and high nutrient inputs can stunt and kill those plants. The performance of *Typha latifolia* monocultures had similar performance to mixture of plants, overall (Fraser *et al.*, 2004).

The literature provides a practical set of conclusions. First, plants are important to subsurface flow constructed wetlands because of the following reasons:

1. Wetland plant roots provide a structure for microorganisms to adhere to and perform processes necessary for transformation of nutrients.
2. Wetland plants allow oxygen transfer through their roots, thus increase levels of oxygen and promoting the oxidation of toxic substances such as ammonia.
3. Wetland plants uptake influent water and are able to remove it through evapotranspiration, thus decreasing effluent quantities.
4. Wetland plants reduce the heat-loss effects of wind and by insulating the wetland from cold temperatures.

Conclusions can also be drawn from literature regarding qualities of most desirable wetland plants to be used in a subsurface constructed wetland application:

1. Wetland plants with robust biomass production are favored over those which produce less biomass. Greater root systems foster a greater metabolizing habitat for bacteria within the root zone.

2. Seasonal temperatures affect oxygen presence for microbes in the root zone. The winter season is the limiting season, and wetland plants with least effect in performance during this season are best.
3. Wetland plants that are perennial, establish quickly, and process a lot of energy while out-competing other wetland or invasive species will thrive in a constructed wetland system with increased nutrient levels in influent streams.

Plant species selection for a subsurface constructed wetland is crucial in order to be able to achieve desired effluent results. Literature suggests that the most desirable plant geneses for wastewater treatment through wetland technology are *Carex* and *Scirpus*.

6.5 CASE STUDY VS LITERATURE REVIEW

Before embarking on the Greenfield project, an existing wetland facility was examined for experience. The France Park case study, presented in Appendix A, supports the conclusions of the literature that has been reviewed. Removal capabilities of ammonia from the wetland cells at France Park were found to be very good for the most part, with capabilities as high as 99.4%. It was observed that the plants with the largest root systems were of the *Carex* and *Scirpus* geneses. This information is particularly relevant to the conclusions drawn from the literature stating that, based on water treatment capabilities, the *Carex* and *Scirpus* geneses would be the best choices for subsurface wetland application. The water treatment results along with an analysis of the plants from the subsurface constructed wetland system at France Park show the qualitative and quantitative results to support the conclusions that plants of the *Carex* and *Scirpus* genus are greatly effective at treating wastewater.

Although the concept of specific plant orientation among mixed cultures of wetland plants was not explicitly discussed in any literature, conclusions may be drawn from the case study and supplemented by results from other studies. Orienting the two species of plants in a specific and separate arrangement within the same wetland cell prevents two problems that inhibit productivity. Taller or larger plants pose problems to smaller plants in that if they grow tall, they shade the lower plants, thus causing plant stress. Plants with larger or deeper root systems also affect plants with smaller or shallower root systems in that deeper or larger root systems take away water and nutrients from plants that have shallower and smaller root systems. Additionally, species with shallow root systems have to compete with invasive plant species that essentially begin their growth by drawing water and nutrients from the uppermost level of water and nutrients. Within a constructed wetland cell, these issues are important because competition between plants can ultimately lead to the extinction of certain wetland plants within wetland cells as has been noticed at the Greenfield rest area. Species that are planted and then lost due to these reasons are effectively a waste of money and are detrimental to the nutrient removal efforts of other more effective plants, which also could have been planted in place of the ineffective species.

CHAPTER 7

TREATMENT PERFORMANCE

7.1 FLOW CHARACTERISTICS

Flow data throughout the wetland system has been collected from the time the system was constructed and outfitted with the flow measuring devices. Over the study period, however, flow data collection was not entirely consistent. For example, some periods of flow data collection had intervals as frequently as one minute, while other data were gathered based on five minute intervals or as daily averages. Moreover, there were periods of time that some flow measuring equipment was out of commission. No flow data was available as a result (for example, from January to July of 2006). In addition to flow data being available sporadically and recorded in an inconsistent matter, there are instances where the data is erroneous due to errors in the flow reading capability of the equipment or mechanical errors causing unwanted flow conditions through the wetland system.

In order to use the available flow data appropriately with the treatment data, flow conditions were observed during a five day window around the date of wastewater sampling for each sampling point. The flow data for a given date is an average daily flow rate calculated from of the best available data from the day of a sampling date, two days before that day, and two days after. This method of determining the flow rate for a given sampling day helps alleviate the errors of possible erroneous data, and also provides a probable flow rate for a sampling day when the actual flow data was not available.

One of the greatest errors in flow data was found in the data collected from flow meter F-3, measuring flow directly out of wetland cell W-3. Errors in data collected from flow meter F-2 were also observed. These errors were due observed flow values being within ranges where instrumental error tends to be the highest. As an alternate method of determining flow out of wetland cell W-3, flow data was estimated for this point in the system through the use of data collected from the weather station and combining it with the data from flow meter F-1, found between the septic tanks. Similarly, flow out of the parallel wetland cells W-1 and W-2 at F-2 was also estimated for this point in the system.

The weather station was able to provide rainfall and evapotranspiration (ETo) data, which was also averaged in the same manner as the flow data over a five day window. Average evapotranspiration and rainfall values were quantified into average daily flows by multiplying their intensities by the combined area of the wetland cells. Taking the average daily flow value from flow meter F-1 and adding the average flow difference resulting from rainfall and evapotranspiration provided a more reliable estimate of the flow rates at F-3 and F-2.

Table 7.1 and 7.2 show a statistical comparison of all average flow data at all possible flow measuring points in the system from all available points correlated with wastewater sampling dates. In some cases, the data varies significantly between the various flow measuring points. For example, the average flow found at the flow meter F-1, between the septic tanks but before recirculation, is 2871 gallons per day (gpd). This value is consistent with surge tank flow readings, but significantly lower than the flow data found at flow meters F-2 or F-3, found directly before and after wetland cell W-3, respectively. The average flow data at F-2 was found to be 7247 gpd and at F-3 was found to be 5320 gpd. This greatly increased flow from the entrance to the system to a point within the system cannot be easily explained. The data from the weather station does not support a claim that infiltration due to rainfall caused such an increase in flow. However, the estimated flow rate ~F3 shows an average daily flow value of 2621 gpd, and the estimated flow rate ~F2 shows an average daily flow value of 2607 gpd, values which are much closer to the 2871 gpd measured at F-1, supporting the estimates as reasonable.

Table 7.1 - Average flow, rainfall, and evapotranspiration data statistics: Metric units

	Average Flow, L/day										mm/day	
Statistic	Surge	F1	M1	M2	F2	F3	M3	M4	~F2	~F3	Rainfall	ETo
Average	8149	10869	66574	22763	27432	20139	1547	21779	9869	9923	3.15	2.28
Maximum	9871	37295	173685	80130	63183	68727	7984	36925	35758	35562	12.60	4.95
Minimum	5548	524	12155	1104	10789	2903	233	11433	134	151	0.00	0.20
Std. Dev.	2292	9518	43304	25913	16287	19971	1893	8527	9530	9554	3.74	1.34

Table 7.2 - Average flow, rainfall, and evapotranspiration data statistics: English units

	Average Flow, gal/day (GPD)										in/day	
Statistic	Surge	F1	M1	M2	F2	F3	M3	M4	~F2	~F3	Rainfall	ETo
Average	2153	2871	17587	6013	7247	5320	409	5753	2607	2621	0.12	0.09
Maximum	2608	9852	45883	21168	16691	18156	2109	9754	9446	9394	0.50	0.19
Minimum	1466	138	3211	292	2850	767	61	3020	35	40	0.00	0.01
Std. Dev.	605	2514	11440	6845	4302	5276	500	2253	2517	2524	0.15	0.05

A final consideration in the flow data was in the differences observed from the surge flow data as compared to that of F-1. The surge tanks became the ultimate flow entrance point into the wetland system. In theory, the flow recorded at the surge tank should be the same as that recorded at F-1, where there is no possibility for infiltration or water loss between these points. However, the data shows that the average daily flow recorded at the surge tank was 2153 gpd while the average daily flow recorded by F-1 was 2871 gpd (refer to Table 7.2). The standard deviations for these average values vary greatly. The standard deviation for the average daily flow of the surge tank is just 605 gpd, while for F-1 the standard deviation is 2514 gpd. Because of this, there were instances where the surge flow data were used in place of F-1 data in calculations involved in changes in mass flux and cumulative contaminant mass removal ratio (explained in detail later this chapter).

In general, variability in the flow data is explained through a number of occurrences. General maintenance and repair may have required flow to the system to be minimized or shut off, thus affecting measured flow values. Temporary flow conditions imposed on the system through the calibration of equipment may also be reflected in the data. Peak flows were experienced at times before surge tank installation, thus imposing high flow readings in the data set.

7.2 WASTE CHARACTERISTICS

The collection of environmental treatment data from various points in the wetland system began after a period of 102 days following the planting of the wetland plants. Until this time (and for some time after this first sampling date, 11/22/2003) the plants were given time to establish themselves in the wetland cells while subject to steady flow conditions (the cyclic fill and draw option was not used). The methods of sample collection and methods of analysis of samples are discussed in Chapter 6. The treatment quality performance indicators that were examined in the wastewater were BOD_5, TSS, and NH_3-N. In addition, pH was also recorded for each sample taken.

Originally, environmental testing on wastewater samples was only conducted on samples taken from the automated samplers. The data sets for AS-1, AS-2, AS-3, and AS-4 (see Fig. 3.3 for locations) are thus the most complete and contain the greatest number of data points. Wastewater samples from the biofield were not consistently taken until the winter season of 2005-2006, and as such, there are less data points available from the biofield, followed by even less data points at the surge tank. Sampling at the surge tank did not being until after its installation; the first samples were taken in the fall of 2006.

Figure 7.1 shows samples taken on June 15, 2006, from the four automatic samplers, AS-1, AS-2, AS-3, and AS-4. The samples appear to darken in color from AS-1 to AS-3, which may be a reflection of the greater amount of particulate solids suspended in the samples (especially distinct in the sample from AS-3). The sample from AS-4 appears to be clearer and lighter in color, which may be correlated to treatment by wetland cell W-3, decreasing levels of nutrients in the wastestream as well as suspended solids.

Figure 7.1 - Samples from AS-1, AS-2, AS-3 and AS-4 (left to right), 06/15/2006

A statistical analysis of all of the available data points regarding concentrations in mg/l of BOD_5, TSS, and NH_3-N are available in Table 7.3. The average BOD_5 values throughout the system vary in a fashion that would be expected. The highest concentrations of BOD_5 are found in samples taken from the surge tank, where the average value is 430 mg/l BOD_5. The lowest average value is found in samples from the biofield, with an average concentration of 129 mg/l. However, it is important to note that there were multiple occasions where BOD_5 values measured higher in biofield samples than in samples from AS-4, a sampling point that precedes the biofield. With regard to TSS, values throughout the system also vary in a fashion that would be expected. The highest TSS values are found in the samples from the surge tank, where the average value is 175 mg/l TSS. The lowest average value is found in samples from the biofield, with an average concentration of 22 mg/l TSS.

Table 7.3 - Average pollutant concentration statistics at sampling points

Pollutant	Statistic	ST	AS1	AS2	AS3	AS4	BF
BOD_5 mg/l	Average	430	337	234	195	147	128
	Maximum	444	396	300	259	226	155
	Minimum	417	260	122	90	82	105
	Std. Dev.	14	38	61	80	40	66
TSS mg/l	Average	175	139	87	73	37	22
	Maximum	183	220	144	216	60	31
	Minimum	165	65	40	32	12	6
	Std. Dev.	64	26	24	43	14	12
NH_3-N mg/l	Average	183	194	132	126	106	105
	Maximum	204	314	203	184	206	179
	Minimum	157	35	30	39	30	0
	Std. Dev.	68	56	48	59	40	62

Average ammonia-nitrogen concentrations show a unique trend among the sampling points. The second sampling point, AS-1, proved to have a greater average concentration of NH_3-N than the samples taken from the surge tank, which precedes AS-1. This could be due to the fact that there is a much smaller pool of data points available from the surge tank, and more data needs to be collected in order to have a more accurate average value. The wastewater collected in the septic tanks may have a prolonged residence time in an absence of oxygen that causes ammonia levels to rise. Thus, it is possible that a wastewater sample taken as AS-1 (between the septic tanks) may in fact contain more NH_3-N than a sample from the surge tank. It is important to note that the recirculation line connects to the system between the septic tanks ST-1 and ST-2, however, after the automated sampler. The lowest average ammonia-nitrogen concentrations also have significant results. Table 7.3 shows that the average concentration of NH_3-N is almost equal at samples taken from AS-4 and the biofield, with concentrations of 106 and 105 mg/l, respectively. It is important to note that the standard deviation of the data from the biofield with regard to NH_3-N is also higher than that of the data from AS-4, with values of 62 and 40 mg/l, respectively. This observation in the statistical analysis of the data is contrary to the assumption that NH_3-N levels would decrease through the use of the biofield.

Regarding pH measurements taken throughout the system, all were generally closely related to each other. An average pH for any given point within the system fell between 7 or 8, with outliers being rather uncommon. Because the pH data was normal as compared to standard pH levels of wetlands and because pH did not change significantly at sampling points throughout the study period, it can be presumed that pH did not have a significant impact on the removal capability of the wetland system. The influence of pH seems to have been minimal and did not change over the course of time.

7.3 ANALYSIS CRITERIA

To best utilize the available flow and wastewater treatment data, four significant analysis criteria were determined and applied to six different scenarios to determine the treatment capabilities of the system. Figures presenting data include best fit lines to illustrate trends in data. The slopes of the best fit lines were analyzed for significant differences from zero through standard analysis of variance (ANOVA) calculations. A slope significantly different from zero suggest that, at 95% confidence, the change in the dependant variable is significant over a period of time.

7.3.1 CONCENTRATION REMOVAL

This criterion evaluates pollutant concentration removal as a percentage based on differences in concentrations measured between points within the wetland system. Pollutant concentrations have been determined in units of mass of contaminant per volume of wastewater. This analysis criteria shows how these values differ in a given wastewater sample set, thus measuring treatment performance based on concentrations.

7.3.2 MASS FLUX REDUCTION

This analysis criterion first combines flow data with contaminant concentration data to determine levels of pollutants as masses per day at various points. By comparing mass flux entering the system and mass flux exiting the system between given points, it is possible to measure treatment performance based on the percentage reduction in mass flux through the system.

7.3.3 FLOW REDUCTION

This criterion evaluates flow reduction as a percentage based on differences in measured flow values between points within the wetland system. This analysis criteria is an indicator of system performance.

7.3.4 SEASONAL VARIATION

This criterion combines the independent variable of time with the concentration removal data in order to show seasonal variation in the removal capability of the key pollutants between locations within the wetland system. This analysis criterion shows whether or not there is a dynamic trend present in pollutant concentration removal. Seasons were determined as shown in Table 7.4.

Table 7.4 - Seasons

Season	Start	End
Winter	December 15	March 14
Spring	March 15	June 14
Summer	June 15	September 14
Fall	September 15	December 14

7.4 CASES EXAMINED

7.4.1 AS-1 - AS-4

This case examines performance of the septic tank along with the three wetland cells. As was mentioned previously, the data set for automated samplers (AS-1 to AS-4, see Fig 3.3) contains the greatest amount of data points. It is important to mention that obtaining enough data points to determine mass flux reductions was difficult based on the fact that a complete set of flow and contaminant concentration data was required for one given date (data point) in order to perform the necessary calculations. Thus, as this case had the most extensive data set, it was possible to perform a reasonable analysis based on all aforementioned criteria.

Figures 7.2 and 7.3 show trends in percent contaminant concentration removal capability of BOD_5, TSS, and NH_3-N between sampling points AS-1 and AS-4 over time. The slopes of the trend lines in Fig. 7.2 show that, over the entire lifecycle of the wetland system, BOD_5 and NH_3-N concentration removal capability is significant, while TSS removal is not. These trends change if data from “start-up” and “stable” periods are separated, as presented in Fig. 7.3. The start-up period encompasses data from the first year of plant establishment (all data before day 500), while the stable period includes any data collected after that first year (after day 500). The slopes of all trend lines during the first year are significantly different from zero, indicating a start up phase, where the percentage concentration removal capability of the system for all pollutants rises. After

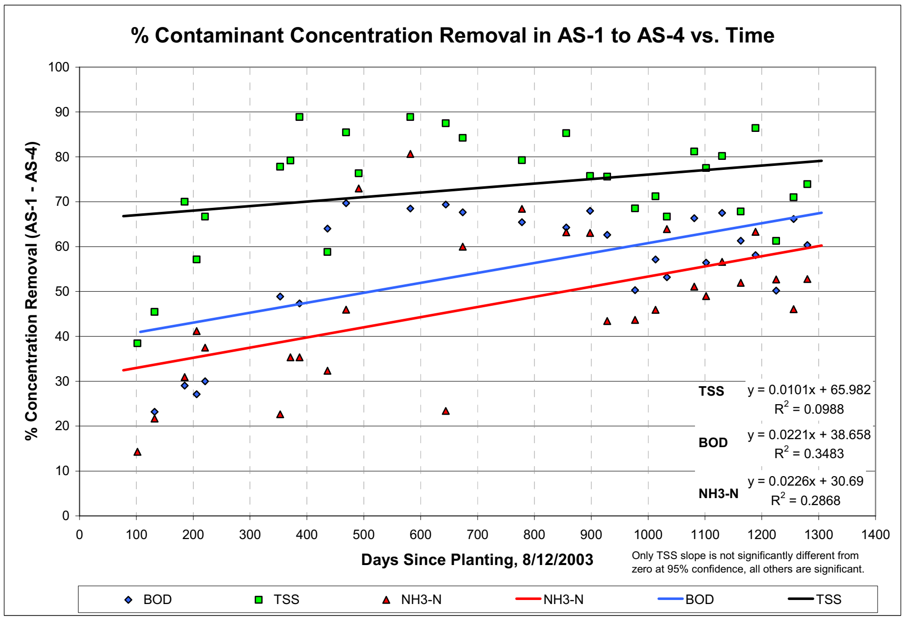


Figure 7.2 - Percentage concentration removal vs. time: AS-1 - AS-4

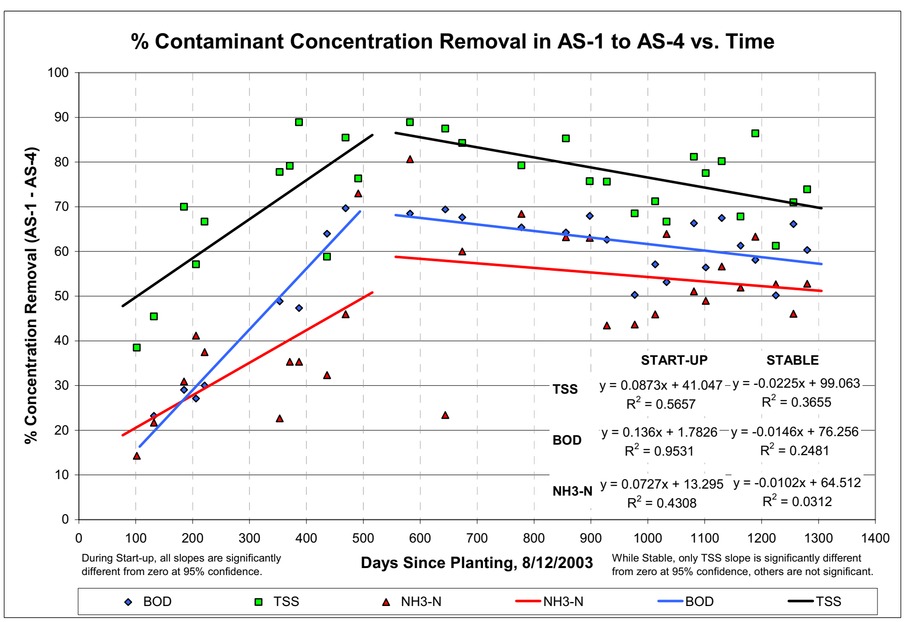


Figure 7.3 - Percentage concentration removal vs. time: AS-1 - AS-4; Start-up vs. Stable

the first year, a stable period is noticed where only TSS shows a significant decrease in removal over time, while slopes of trend lines indicative of BOD_5 and NH_3-N removal are not significantly different from zero. BOD_5 removal percentage peaks at 69.7% on day 469. TSS removal percentage peaks at 88.9% on day 582. NH_3-N removal percentage peaks at 80.7% on day 582. The most recent data points on day 1280 show concentration removal percentages between AS-1 and AS-4 of BOD_5, TSS, and NH_3-N at 60.3%, 73.9%, and 52.8%, respectively.

Figure 7.4 shows average contaminant concentration removal percentages with their standard deviations as a function of season. Greatest removal percentages of concentrations of BOD_5, TSS, and NH_3-N between AS-1 and AS-4 appear to be during the fall, summer, and spring seasons, respectively. Worst removal percentages of concentrations of BOD_5, TSS, and NH_3-N between AS-1 and AS-4 appear to be during the winter, winter, and summer seasons, respectively. Standard deviations and sample numbers, however, show statistically significant differences at 95% confidence only between the winter and fall seasons in BOD_5 and only in winter and summer in TSS, with no statistical significant differences in seasonal ammonia-nitrogen removal.

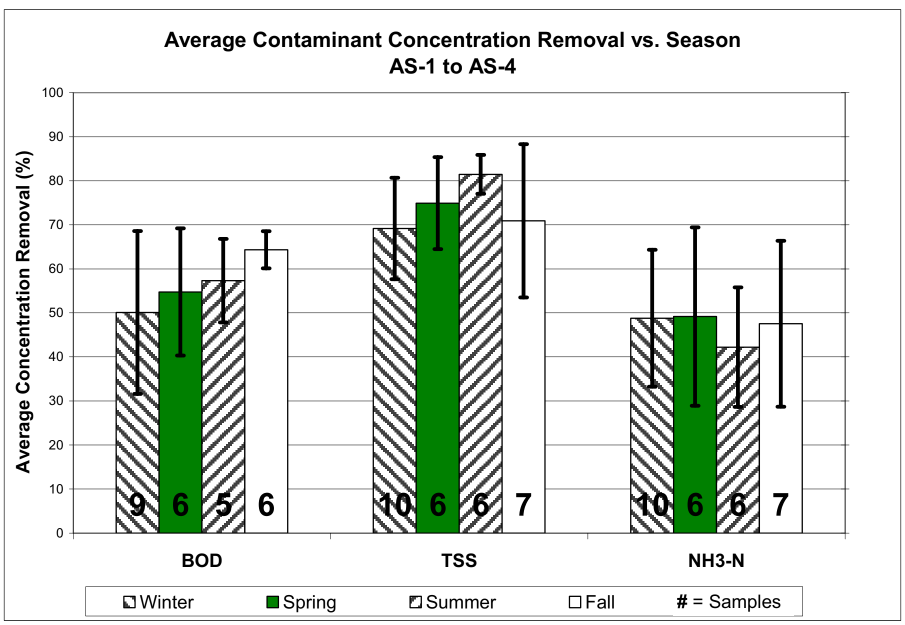


Figure 7.4 - Average concentration removal vs. season: AS-1 - AS-4

Figures 7.5 and 7.6 shows percentage changes in contaminant mass flux between AS-1 and AS-4 over time. The slopes of the trend lines in Fig. 7.5 show that, over the entire lifecycle of the wetland system, BOD_5 and NH_3-N mass flux reduction capability is significant, while TSS reduction is not. These trends change if data from start-up and stable periods are separated, as presented in Fig. 7.6. The slopes of all trend lines before day 500 are significantly different from zero, indicating a start up phase, where the mass flux reduction capability of the system for all pollutants rises. After day 500, a stable period is noticed where only NH_3-N shows a significant decrease in removal over time, while slopes of trend lines indicative of BOD_5 and TSS removal are not

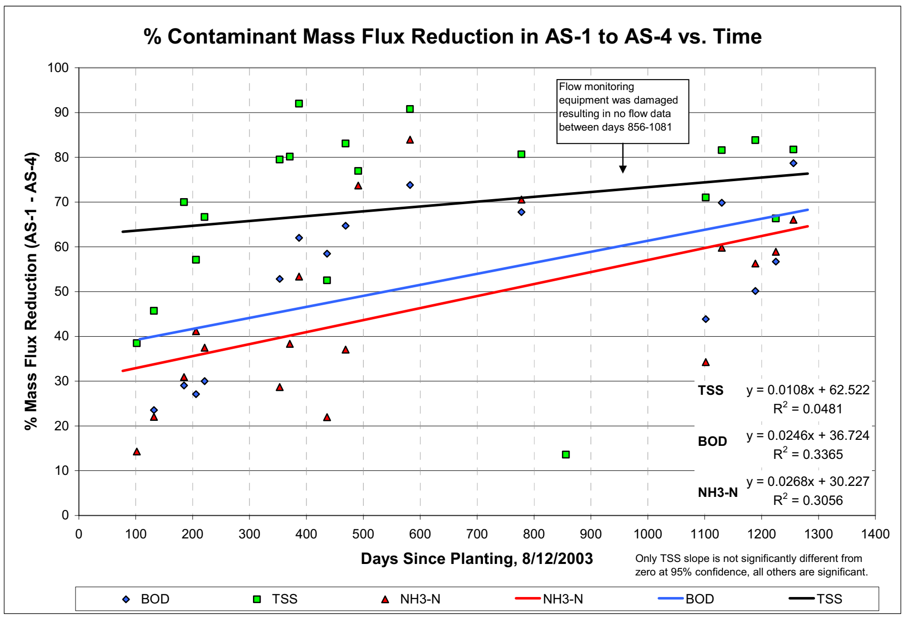


Figure 7.5 - Mass flux reduction vs. operational days: AS-1 - AS-4

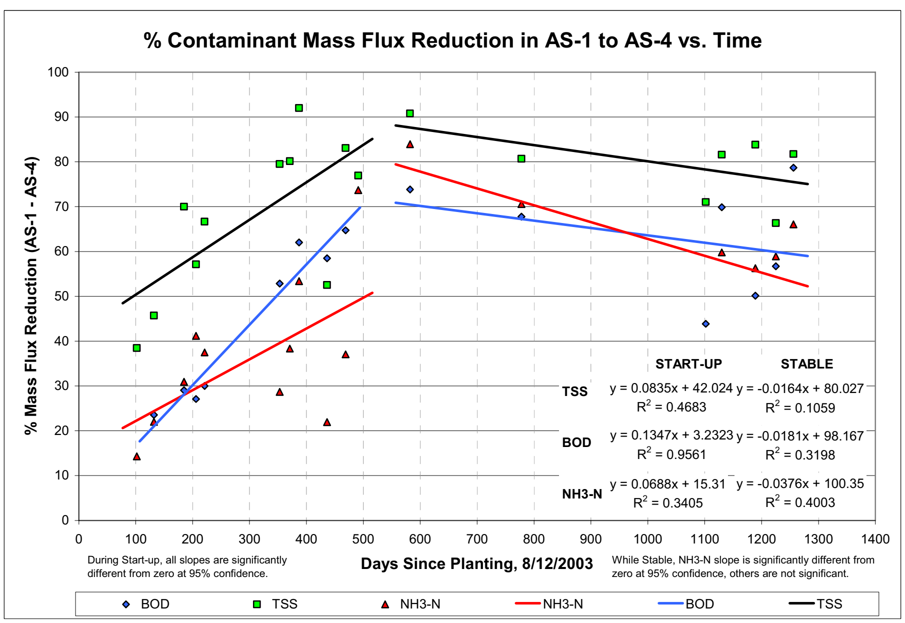


Figure 7.6 - Percentage mass flux reduction vs. operational days: AS-1 - AS-4; Start-up vs. Stable

significantly different from zero. The highest values of percentage removal of mass flux for BOD_5, TSS, and NH_3-N for this case are 78.7%, 92.0%, and 83.9%, respectively. The lowest values all fall below 25%.

Figure 7.7 shows flow reduction capability between AS-1 and AS-4 over time. The slope of the best fit line through this data is not significantly different from zero, indicating that flow reduction over time was relatively stable. Variance in the flow reduction data is somewhat high. The highest amount of flow reduction was recorded on day 1189, where 81.0% of the flow was reduced. Negative flow reductions indicate that flow was increased through the system; the highest flow increase appeared on day 308, where flow was increased by 85.7%. The possibility for such variances in flow data was explained in Section 7.1, describing flow characteristics.

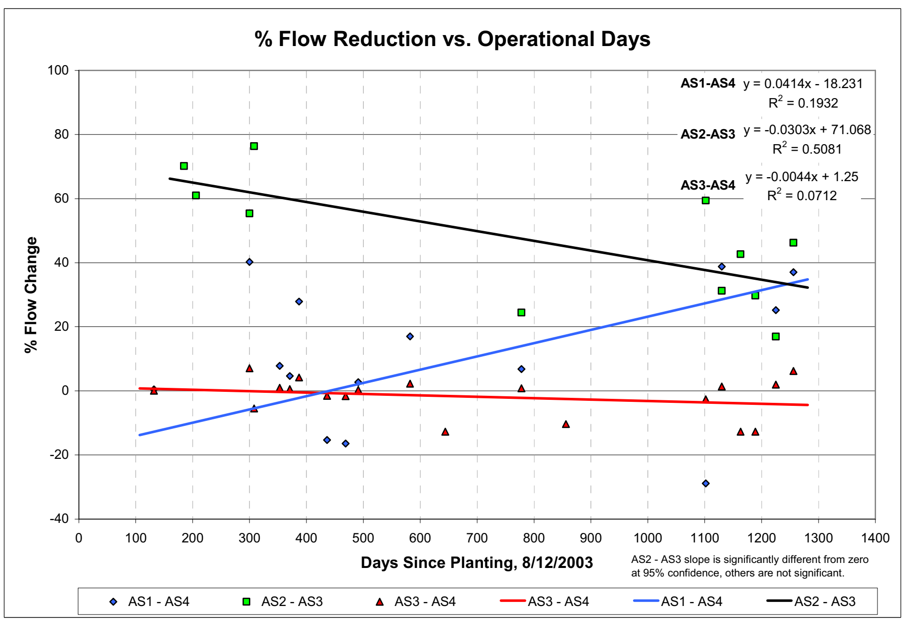


Figure 7.7 - Percentage flow reduction vs. operational days

7.4.2 AS-1 - BIOFIELD

This aspect includes the septic tank, wetland cells, and the biofield as a system. The data set for the biofield does not begin until well after the system was established in the winter spanning 2005-2006. As a result of the lack of adequate data, this case was examined based on contaminant concentration removal and seasonal variation, excluding contaminant mass flux reduction and flow reduction calculations. It is important to mention that two shallow wells for sample acquisition were always dry. Samples could only be obtained from the third well, which allowed for the extraction of a sample from the deepest portion of the biofield.

Figure 7.8 shows trends in percent contaminant concentration removal capability of BOD_5, TSS, and NH_3-N between sampling points AS-1 and the biofield over time. Over the period of available data, the trends in concentration removal of all pollutants show little change over time. The slopes of the trend lines in Fig. 7.8 show that contaminant concentration removal capability of the system between AS-1 and the biofield does not significantly change with time. BOD_5 removal percentage peaks at 70.2% on day 1256. TSS removal percentage peaks at 95.9% on day 1033. NH_3-N removal percentage peaks at 66.1% on day 1033. The lowest concentration removal percentages appear to 57.4%, 76.0%, and 33.8% for BOD_5, TSS, and NH_3-N, respectively.

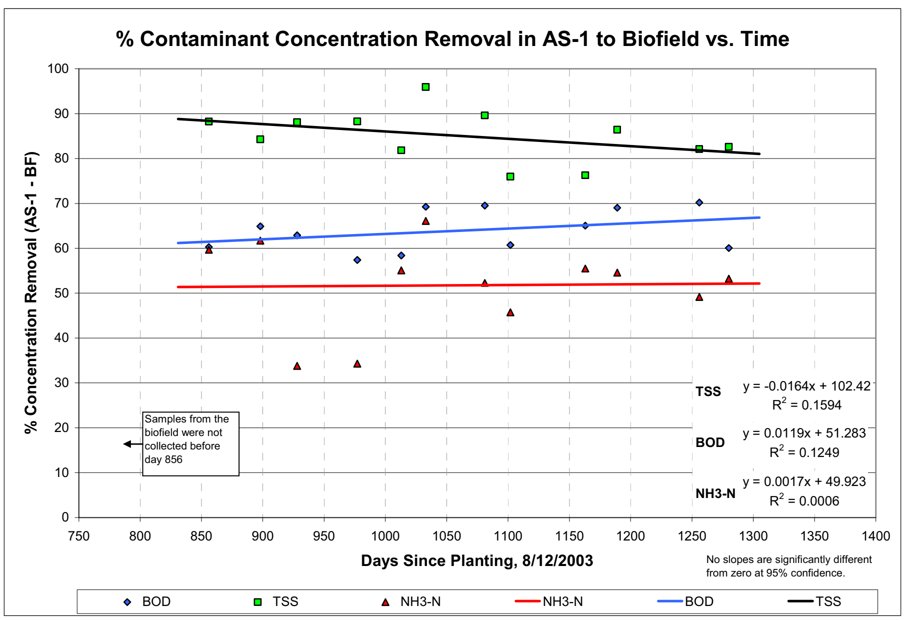


Figure 7.8 - Percentage concentration removal vs. operation days: AS-1 - Biofield

Figure 7.9 shows average contaminant concentration removal percentages with their standard deviations as a function of season. Greatest removal percentages of concentrations of BOD_5, TSS, and NH_3-N between AS-1 and the biofield appear to be during the fall, spring, and fall seasons, respectively. Worst removal percentages of concentrations of BOD_5, TSS, and NH_3-N between AS-1 and the biofield appear to be during the spring, fall, and summer seasons, respectively. Standard deviations and sample numbers, however, show no statistically significant differences at 95% confidence and a significant difference only between summer and fall at 90% confidence.

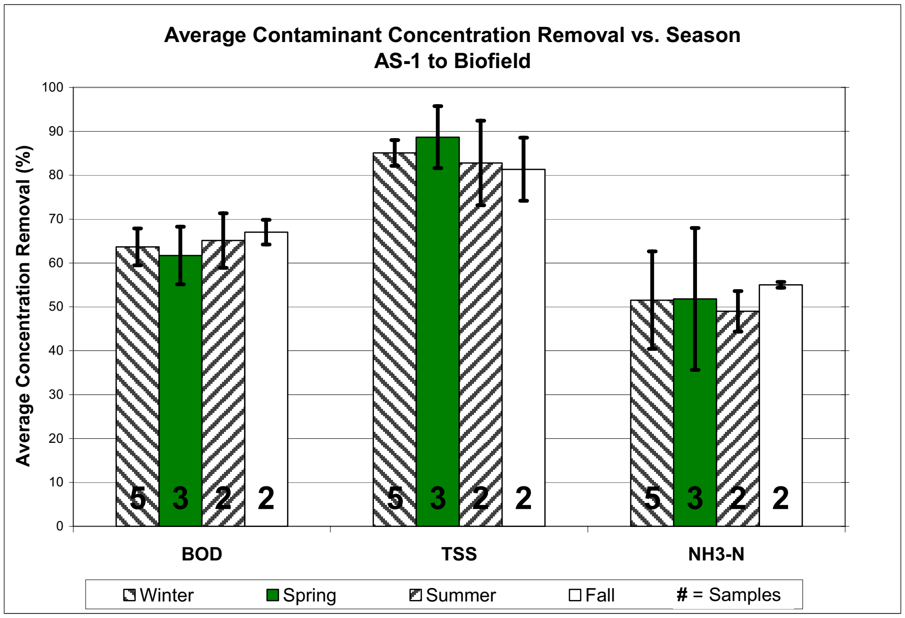


Figure 7.9 - Average concentration removal vs. season: AS-1 - Biofield

7.4.3 AS-4 - BIOFIELD

This case isolates the performance of the biofield alone. The data set for the biofield does not begin until well after the system was established in the winter spanning 2005-2006. As a result of the lack of adequate data, this case was examined based on contaminant concentration removal and seasonal variation, excluding contaminant mass flux reduction and flow reduction calculations.

Figure 7.10 shows trends in percent concentration removal capability of BOD_5, TSS, and NH_3-N between sampling points AS-4 and the biofield over time. Over the period of available data, the trends in concentration removal of all pollutants show little change over time. The slopes of the trend lines in Fig. 7.10 show that contaminant concentration removal capability of the system between AS-1 and the biofield does not significantly change with time. BOD_5 removal percentage peaks at 34.4% on day 1033. TSS removal percentage peaks at 87.8% on day 1033. NH_3-N removal percentage peaks at 16.9% on day 1013. These concentration removal percentages appear to be very low when compared other cases examined. It is important to note that many negative changes were recorded for this case, especially with regard to NH_3-N removal. This means that the concentration of ammonia-nitrogen actually increased between these two consecutive points in the system.

Figure 7.11 shows average contaminant concentration removal percentages with their standard deviations as a function of season. Greatest removal percentages of concentrations of BOD_5, TSS, and NH_3-N between AS-4 and the biofield appear to be

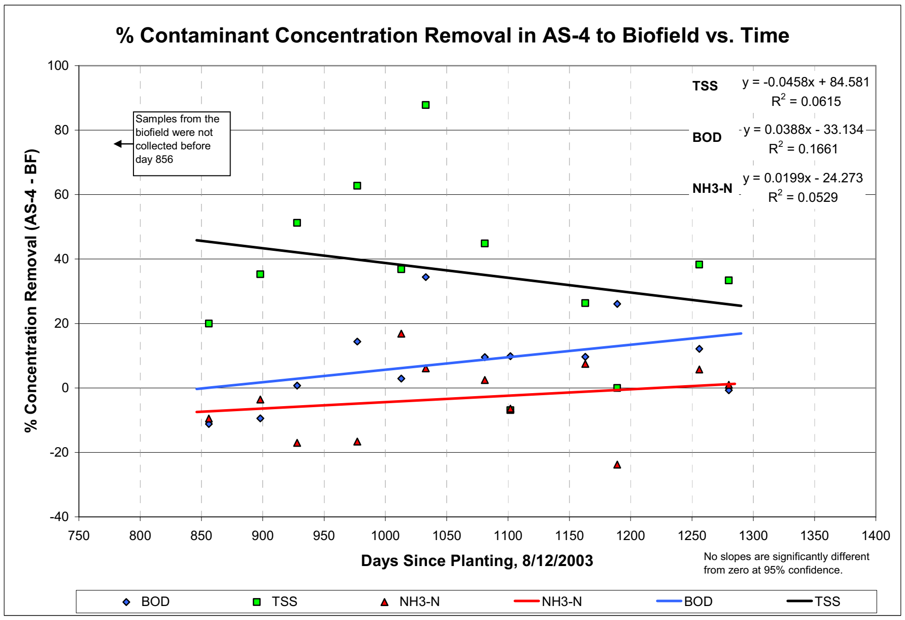


Figure 7.10 - Percentage concentration removal vs. operation days: AS-4 - Biofield

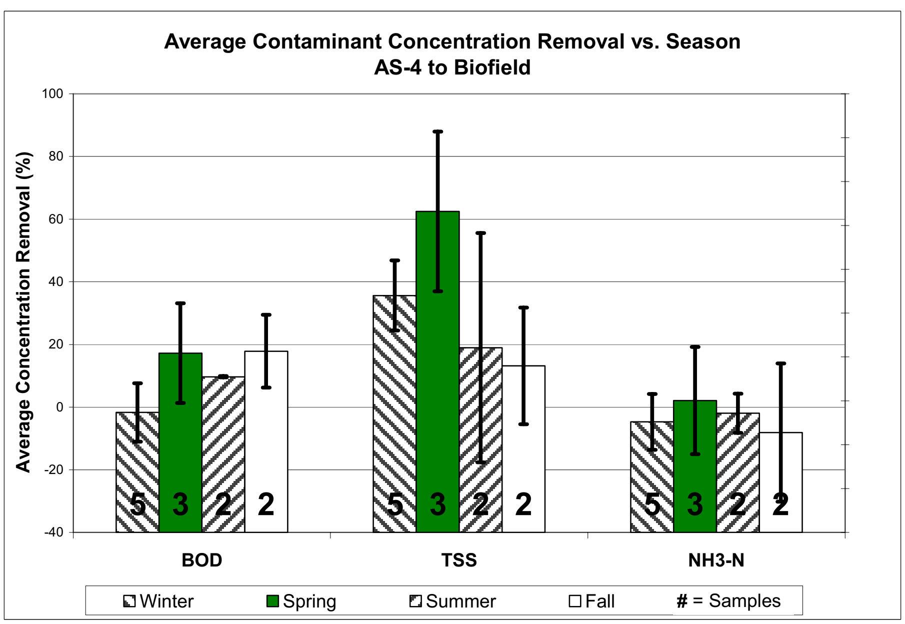


Figure 7.11 - Average concentration removal vs. season: AS-4 - Biofield

during the fall, spring, and spring seasons, respectively. Worst removal percentages of concentrations of BOD_5, TSS, and NH_3-N between AS-4 and the biofield appear to be during the winter, fall, and fall seasons, respectively. Standard deviations and sample numbers, however, show statistically significant differences at 95% confidence only between winter and summer and winter and fall in BOD_5, and only in spring and fall in TSS, with no statistical significant differences in seasonal ammonia removal. At 90% confidence there is additional significant difference between winter and spring for both BOD_5 and TSS, with no significant seasonal difference in ammonia removal.

7.4.4 SURGE TANK - BIOFIELD

With the inclusion of the surge tank, this case could examine the entire system. The surge tank was installed in the summer of 2006 to help eliminate peak flows into the wetland system and to help stabilize flow patterns. The data set for the biofield does not begin until the winter spanning 2005-2006. The data set for the surge tank begins in the fall of 2006. As a result of the lack of adequate data, this case was examined based on contaminant concentration removal and seasonal variation, excluding contaminant mass flux reduction and flow reduction calculations.

Figure 7.12 shows trends in percent concentration removal capability of BOD_5, TSS, and NH_3-N between the surge tank and the biofield over time. Over the period of available data, the trends in concentration removal of all pollutants show little change over time. The slopes of the trend lines in Fig 7.12 show that contaminant concentration removal capability of the system between the surge tank and the biofield does not significantly change with time. However, strong conclusions cannot be drawn as the data is too sparse. Average removal percentage of BOD_5, TSS, and NH_3-N are 72.1%, 85.7%, and 42.6%, respectively. Because there are only four data points for this analysis, high and low values do not disclose enough information. However, the standard deviations for these values are also very small, all under 6.5%. It is important to note, again, that these values are based on a limited amount of data and only during a period after system establishment.

Figure 7.13 shows average contaminant concentration removal percentages with their standard deviations as a function of season. Because of the limited amount of data (only two points per season per contaminant), a comparison can only be presented between the winter and fall seasons (when samples were collected). There are no statistically significant differences at 95% or 90% confidence for any of situations.

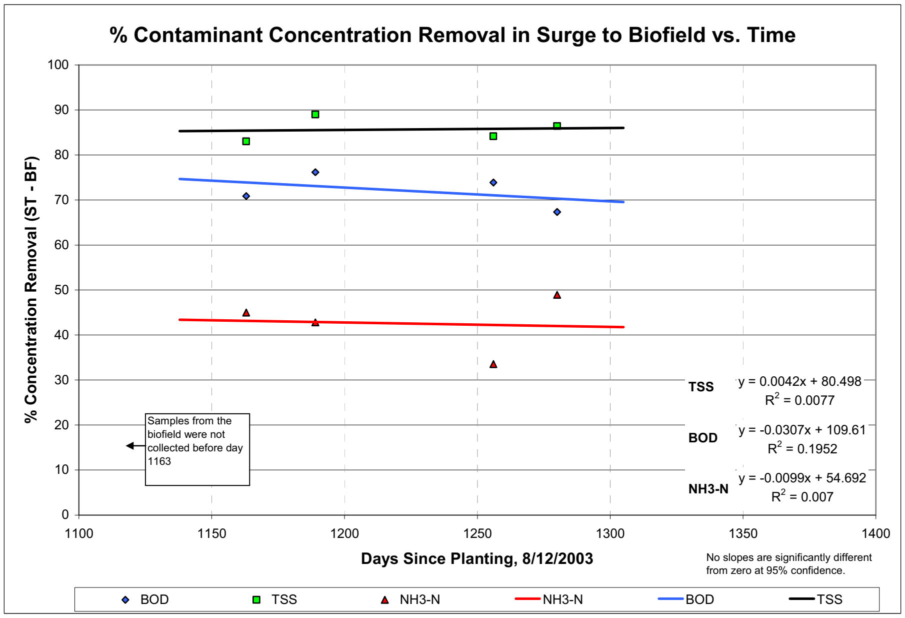


Figure 7.12 - Percentage concentration removal vs. operation days: Surge Tank - Biofield

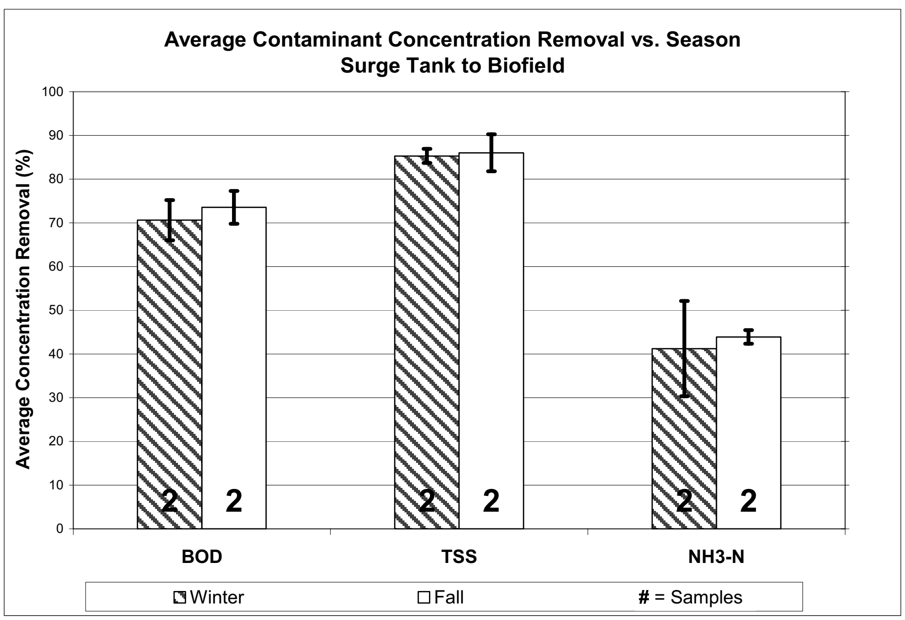


Figure 7.13 - Average concentration removal vs. season: Surge Tank - Biofield

7.4.5 AS-2 - AS-3

This case, similar to the case analyzing treatment capabilities of AS-3 - AS-4, is unique in that it isolates the removal capability of only one main system component - the parallel wetland cells W-1 and W-2. Environmental quality data is available for both AS-2 and AS-3 after day 353. However, for a period of time after between day 353 and 778, hydraulic data was not available due to maintenance and repair issues with the flow measuring equipment. This case was examined based on concentration removal, seasonal variation, and mass flux reduction, and flow reduction with the available data.

Figures 7.14 and 7.15 show trends in percent contaminant concentration removal capability of BOD_5, TSS, and NH_3-N between sampling points AS-2 and AS-3 over time. Sampling wasn't possible before day 353 due to the samplers being inaccessible. The data set in Fig. 7.14 begins after day 353 and includes all available data for AS-2 and AS-3 sampling after this time. None of the slopes of the trend lines are significantly different from zero at 95% confidence. These trends change, however, if data from "start-up" and "stable" periods are separated, as presented in Fig. 7.15. The start-up period, before day 500, does not encompass enough data to justify its analysis. After day 500, during the stable period, NH_3-N and TSS show a significant decrease in removal over time, while the slope of the trend line indicative of BOD_5 removal is not significantly different from zero. BOD_5 removal percentage peaks at 31.9% on day 436. TSS removal percentage peaks at 60.9% on day 582. NH_3-N removal percentage peaks at 56.9% on day 644.

Figure 7.16 shows average concentration removal percentages with their standard deviations as a function of season. Greatest removal percentages of concentrations of

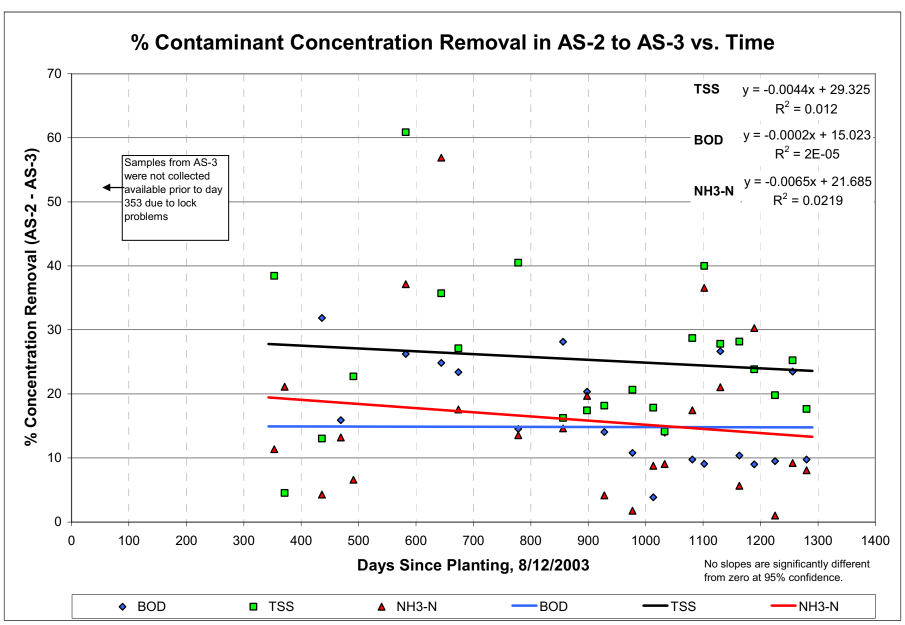


Figure 7.14 - Percentage concentration removal vs. operation days: AS-2 - AS-3

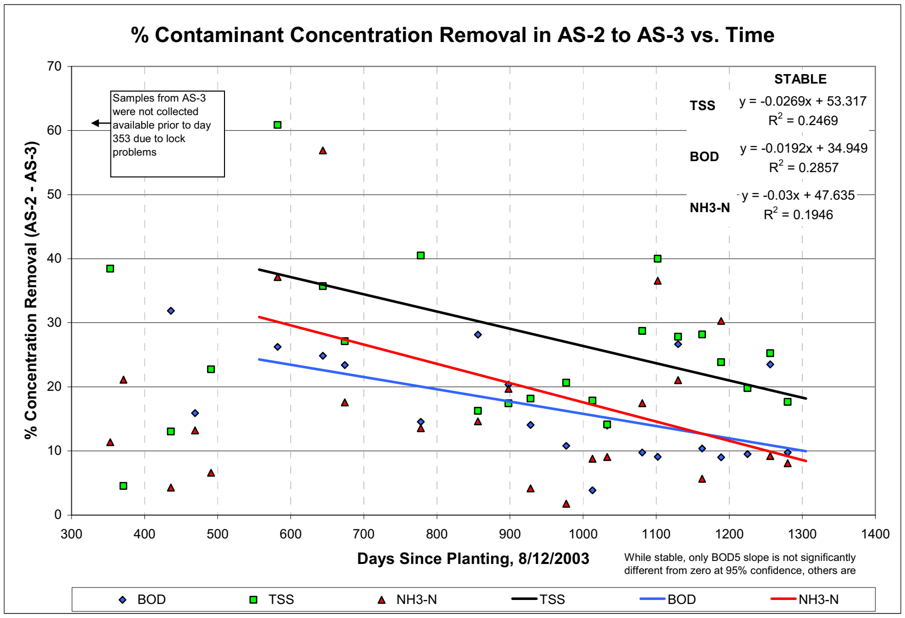


Figure 7.15 - Percentage concentration removal vs. operation days: AS-2 - AS-3; Start-up vs. Stable

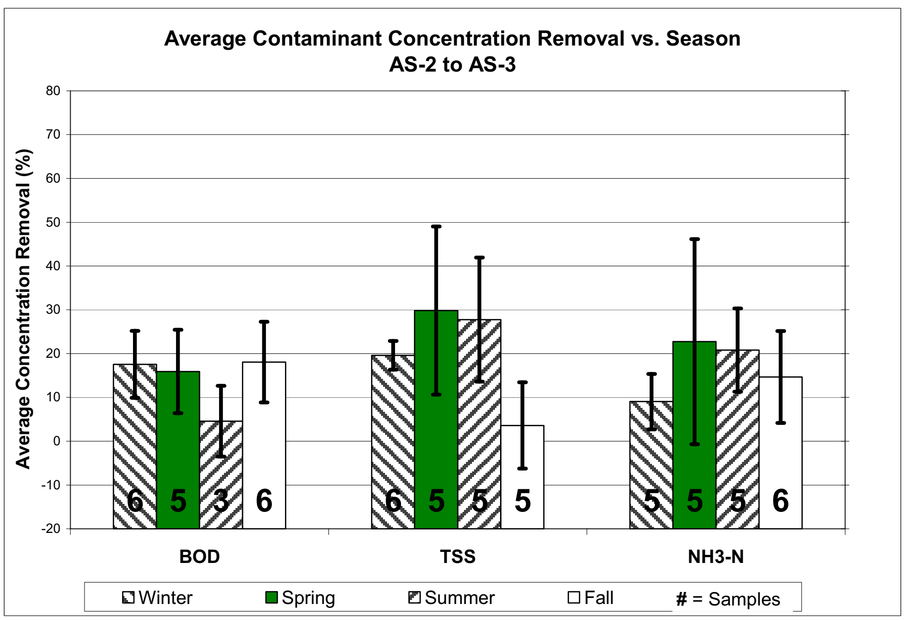


Figure 7.16 - Average concentration removal vs. season: AS-2 - AS-3

BOD_5, TSS, and NH_3-N between AS-2 and AS-3 appear to be during the fall, spring, and spring seasons, respectively. Worst removal percentages of concentrations of BOD_5, TSS, and NH_3-N between AS-2 and AS-3 appear to be during the summer, winter, and winter seasons, respectively. Standard deviations and sample numbers, however, show the only statistically significant difference at 95% confidence between winter and summer in NH_3-N, with no statistical significant differences in seasonal BOD_5 or TSS removal, and no significant differences at 90% confidence.

Figure 7.17 shows percentage changes in contaminant mass flux between AS-2 and AS-3 over time. No data points before day 778 are available due to the unavailable environmental data before day 353 and unavailable hydraulic data between days 353 and 778. Thus, the available data falls within the "stable" period of the wetland. None of the slopes of the trend lines in Fig. 7.17 are significantly different from zero. The highest values of percentage removal of mass flux for BOD_5, TSS, and NH_3-N for this case are 79.4%, 77.9%, and 98.3%, respectively. It is important to note, however, that the variance in the BOD_5 and TSS data points is fairly significant, as the lowest values fall to 12.4% for TSS and 1.2% for BOD_5. These low values are present within the last year of sampling.

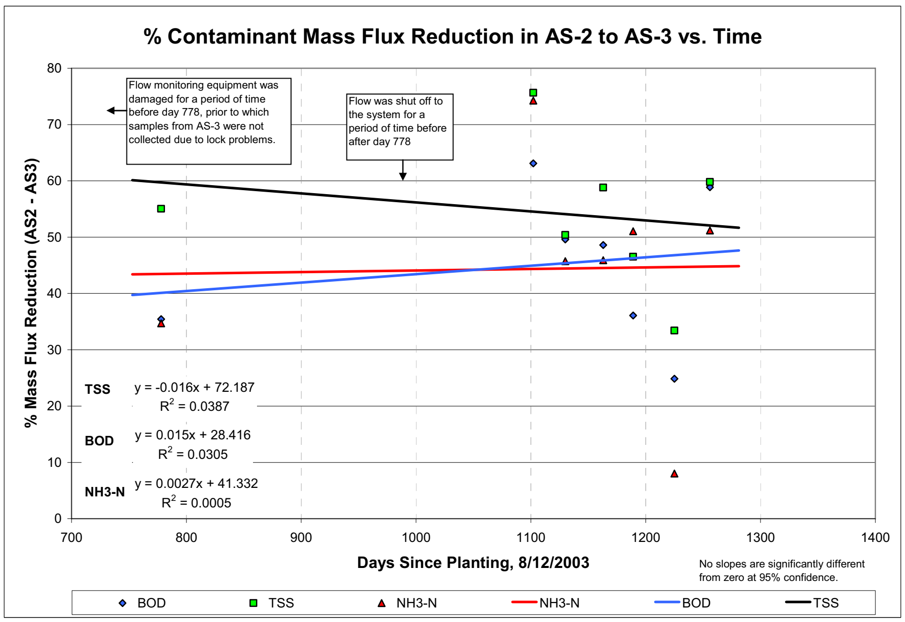


Figure 7.17 - Percentage mass flux reduction vs. operational days: AS-2 - AS-3

Figure 7.7 shows flow reduction capability between AS-2 and AS-3 over time. Hydraulic data between days 353 and 778 was unavailable. However, the available data spans both the start-up and stable periods of the lifetime of the wetland system. The slope of the best fit line through the available data is significantly different from zero, indicating that flow reduction capability over time decreased in this case. The highest amount of flow reduction was recorded on day 308, where 76.4% of the flow was reduced; the lowest flow reduction was recorded on day 1225, where 16.9% of the flow was reduced.

7.4.6 AS-3 - AS-4

This case, similar to the case analyzing treatment capabilities of AS-2 - AS-3, isolates the removal capability of only one main system component - the “polishing” wetland cell W-3. Much data is available for AS-3 and AS-4, as sampling from these stations began at the earliest stages of research. However, for a period of time before day 353, environmental quality data was not available. This case was examined based on concentration removal, seasonal variation, and mass flux reduction, and flow reduction with the available data.

Figures 7.18 and 7.19 show trends in percent contaminant concentration removal capability of BOD_5, TSS, and NH_3-N between sampling points AS-3 and AS-4 over time. Sampling wasn’t possible before day 353 due to the samplers being inaccessible. The data set in Fig. 7.18 begins after day 353 and includes all available data for AS-3 and AS-4 sampling after this time. The slopes of the trend lines in Fig. 7.18 show that, over the period of time encompassing the “start-up” and “stable” periods, BOD_5 and NH_3-N concentration removal capability is significant and increases over time, while TSS removal does not significantly change. These trends change, however, if data from start-up and stable periods are separated, as presented in Fig. 7.19. The start-up period, before day 500, does not encompass enough data to justify its analysis. After day 500, during the stable period, only BOD_5 shows a significant increase in removal over time, while slopes of trend lines indicative of NH_3-N and TSS removal are not significantly different from zero. BOD_5 removal percentage peaks at 44.2% on day 1163. TSS removal

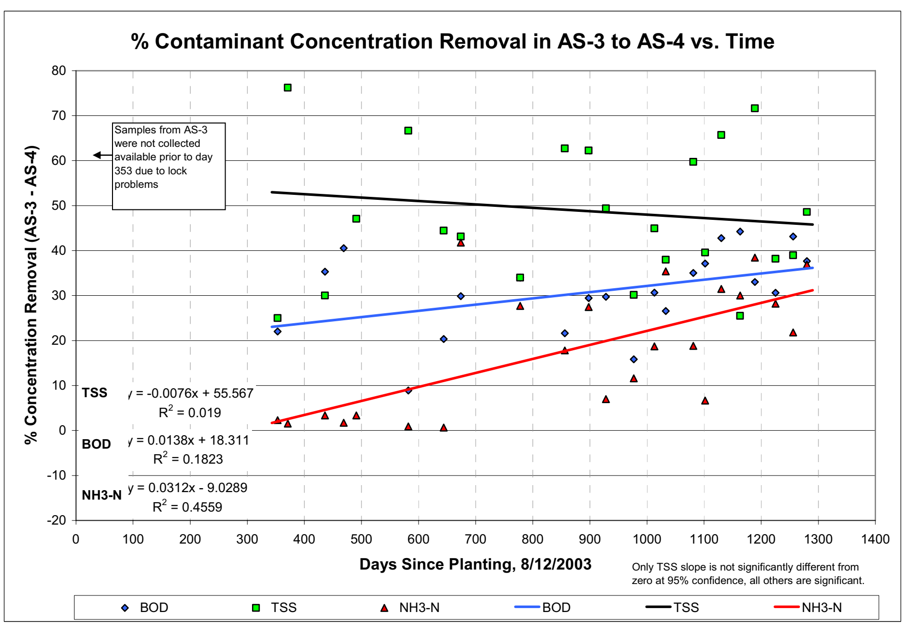


Figure 7.18 - Percentage concentration removal vs. operation days: AS-3 - AS-4

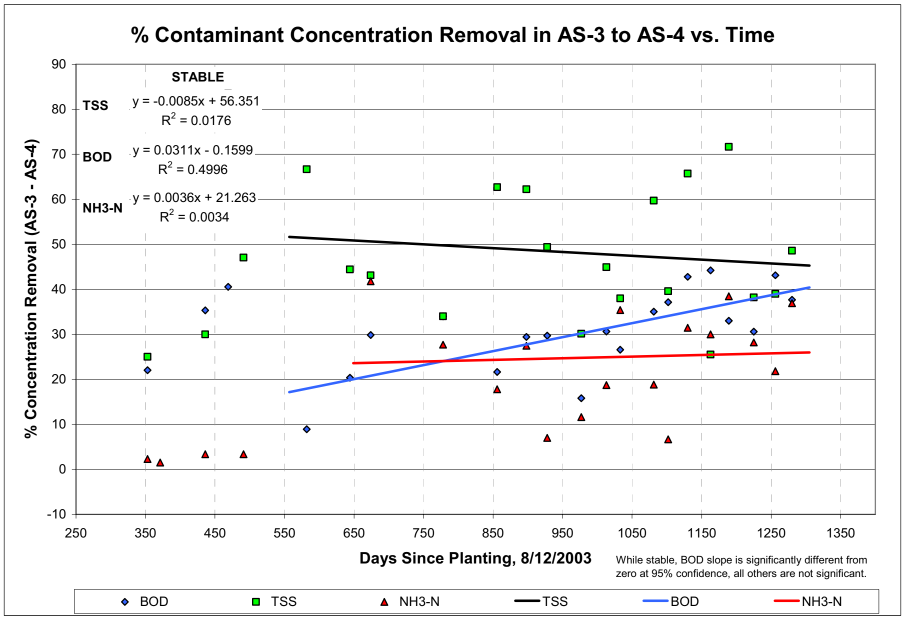


Figure 7.19 - Percentage concentration removal vs. operation days: AS-3 - AS-4; Start-up vs. Stable

percentage peaks at 85.2% on day 469. NH_3-N removal percentage peaks at 41.8% on day 674.

Figure 7.20 shows average contaminant concentration removal percentages with their standard deviations as a function of season. Greatest removal percentages of concentrations of BOD_5, TSS, and NH_3-N between AS-2 and AS-3 appear to be during

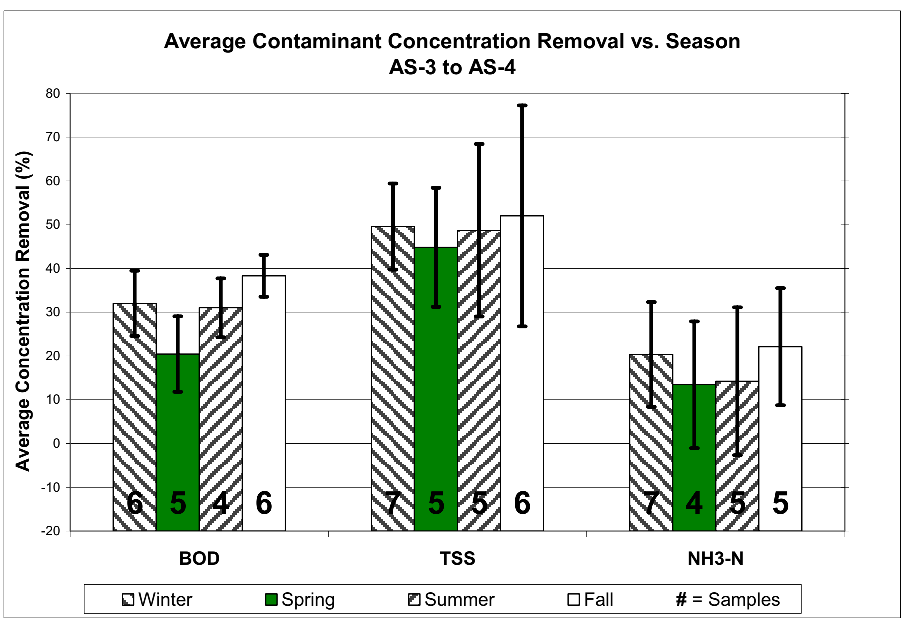


Figure 7.20 - Average concentration removal vs. season: AS-3 - AS-4

the fall, spring, and spring seasons, respectively. Worst removal percentages of concentrations of BOD_5, TSS, and NH_3-N between AS-2 and AS-3 appear to be during the summer, winter, and winter seasons, respectively. Standard deviations and sample numbers, however, show the only statistically significant difference at 95% confidence between winter and summer in NH_3-N, with no statistical significant differences in seasonal BOD_5 or TSS removal, and no significant differences at 90% confidence.

Figures 7.21 and 7.22 shows percentage changes in contaminant mass flux between AS-3 and AS-4 over time. The slopes of the trend lines in Fig. 7.21 show that, over the period of time encompassing the “start-up” and “stable” periods, no change in mass flux reduction capability is significant at 95% confidence. These trends are the same if data from the only the stable period (after day 500) is analyzed, as presented in Fig. 7.22. The highest values of percentage removal of mass flux for BOD_5, TSS, and NH_3-N for this case are 78.7%, 92.0%, and 83.9%, respectively. The lowest values all fall below 25%.

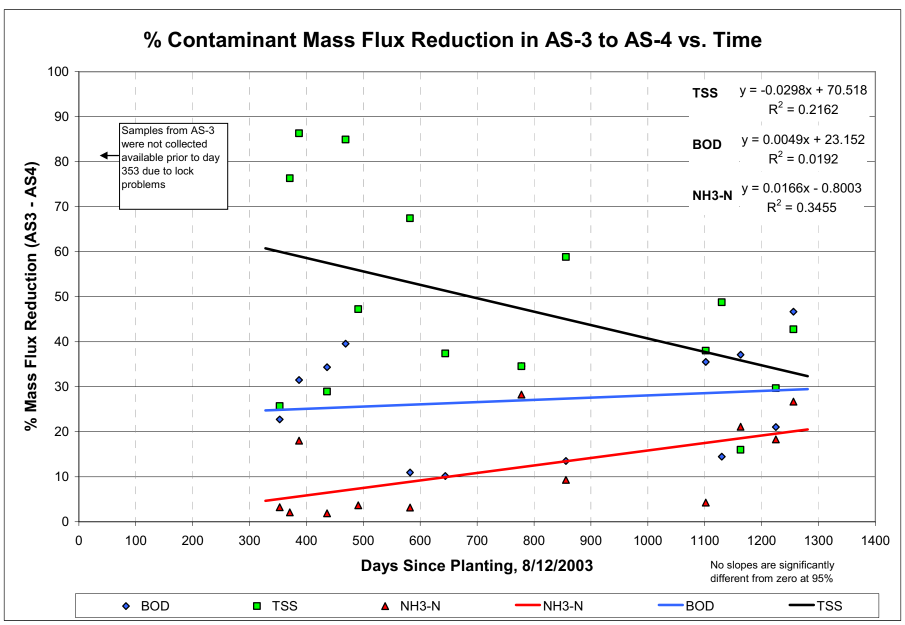


Figure 7.21 - Percentage mass flux reduction vs. operational days: AS-3 - AS-4

Figure 7.7 shows flow reduction capability between AS-3 and AS-4 over time. The available data spans both the start-up and stable periods of the lifetime of the wetland system. The slope of the best fit line through the available data is not significantly different from zero at 95% confidence, indicating that flow reduction capability over time does not change in this case. The highest amount of flow reduction was recorded on day 300, where 7.1% of the flow was reduced. On day 1225, a -12.8% value for flow reduction was calculated. This indicates that flow was gained on that day, which is possible in the event of strong rain.

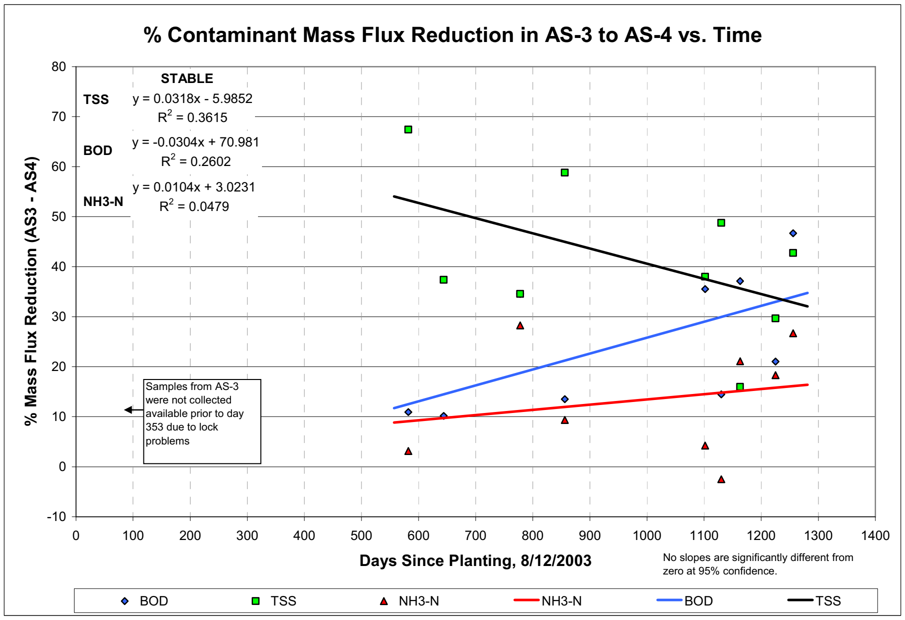


Figure 7.22 - Percentage mass flux reduction vs. operational days: AS-3 - AS-4; Start-up vs. Stable

7.5 WETLAND PLANTS ANALYSIS

The subsurface wetland cells of the system in Greenfield were originally planted with about 13 species of plants (Table 7.5), totaling about 4,000 plants within all cells. All species were planted in a randomly mixed fashion throughout all of the wetland cells. Of these species, observations over the lifetime of the system have shown many of the species to become extinct. After the first winter (2003-04) some of the species planted did not grow in the following blooming season. After the subsequent winter (2004-05), a greater number of invasive species were found in the places of the missing wetland plants, and in the spring of 2006, many invasive species were found mixed with the few wetland species remaining to date.

Wetland plants are essential to the treatment capabilities of the system, owing to their aptitude for providing oxygen to the bacteria that live in the root zone and also as agents of evapotranspiration. Since the original construction of the system, completed in August of 2003, the wetlands have undergone much change with regard to plant media presence, particularly within the parallel wetland cells W-1 and W-2. As the system was modified and upgraded, variability in water flow rate put additional stress on the wetland plants. Many of the species died and/or have been replaced by invasive species. Figure 7.23 shows a progression of the quality and quantity of wetland plants from 2003-2006 in wetland cell 1 (W-1).

Table 7.5 - Wetland vegetation present at the Greenfield facility.]

Latin Name	Also Known As	Common Name	Family	Quantity
Wetland Vegetation through April 2006				
Actinomeris alternifolia	Verbesin alternifolia			4,000 Total
Carex lacustris	Carex riparias	Lake Sedge	Cyperaceae	
Carex vulpinoidea		Fox Sedge	Cyperaceae	
Helenium autumnale		Sneezeweed, Helen's Flower	Asteracea	
Iris virginica shrevei		Blue Flag Iris, Virginia Iris		
Physostegia virginiana			Lamiaceae	
Pontederia cordata			Pontederiaceae	
Sagittaria latifolia		Arrowhead, Wapato, Duck Potato	Alismataceae	
Scirpus cyperinus		Wool Grass	Cyperaceae	
Scirpus fluviatilis		River Bulrush	Cyperaceae	
Scirpus validus creber		Softstem Bulrush	Cyperaceae	
Spartina pectinata		Prarie Codgrass	Poaceae	
Verbena hastate		Blue Vervain	Verbenaceae	
Wetland Vegetation from May 2006 to Present				
Iris versicolor		Wild Iris		200
Sagittaria latifolia		Arrowhead	Alismataceae	50
Saururus cernuus		Lizard's Tail		50
Scirpus validus		Softstem Bulrush	Cyperaceae	100
Carex emoryi		Riverbank Russock Sedge	Cyperaceae	100

Beginning in the summer of 2005, a significant negative trend was observed in the quality of the wetland plants, with a majority of this trend found within wetland cells W-1 and W-2. As a surge tank was being installed to help control flow and eliminate peak flows, water flow to the system was cut off. It was observed that the wetland plants were not blooming as well toward the end of the growing season of 2005 as they were in 2004. Many invasive species began growing in the cells. A photographic comparison of the cells from the dormant season (winter) of 2003-04, 2004-05, and 2005-06, with particular interest in the photos taken on 4/29/2005 and 4/15/2006, shows significant changes in the living biomass above ground in cell W-1. Although the blooming periods for most of the media within the cells begins in May (New, 2006), photographs of the short period preceding the start of the seasonal bloom indicate the quality and quantity of the growing season. The pre-seasonal conditions of the wetland plants in the spring of 2004 and 2005,

	***Day 102*** *11/22/2003*	❖ ***Wetlands planted 08/12/2003 (Day 0)*** ❖ ***Planting in the latter portion of the blooming season*** ❖ ***Minimal growth during remainder of blooming season***
	***Day 259*** *4/29/2004*	❖ Cold temperatures prevented growth and development during winter months ❖ Plants look healthy and ready for spring bloom ❖ Some species are no longer present
	***Day 298*** *6/07/2004*	❖ Seasonal warmth and adequate water and nutrients allow vast growth ❖ Some invasive species are present in the wetland cells
	***Day 434*** *10/21/2004*	❖ End of growing season is approaching ❖ Plants are unhealthy due to lack of steady water flow
	***Day 674*** *6/17/2005*	❖ Plants flourish after winter season ❖ More species are no longer present ❖ Invasive species have increased
	***Day 777*** *9/28/2005*	❖ Flow was minimal/inconsistent during surge tank installation ❖ Plants began dying earlier in this growing season than the previous year ❖ Many dead plants and invasive species were pulled out of the wetland
	***Day 975*** **4/15/2006**	❖ Many wetland plants are missing ❖ Pre-blooming season inspection shows much worse condition of plant media this season than the last

Figure 7.23 - Growth progression of wetland plants in wetland cell 1 (W-1)

showing living biomass, were followed by good growing seasons, resulting from water flow.

As a result of the loss of many of the wetland plants that were originally implemented into the wetland cells, the wetlands were replanted with an assortment of five different wetland species in the spring of 2006. A comparison of the vegetation present in the wetlands before and after the replanting can be seen in Table 7.5. The *Carex lacustris* and *Carex vulpinoidea* species (sedges) were appended with a different sedge species, *Carex emoryi*. The arrowhead species was not changed, retaining *Sagittaria latifolia*. One of the bulrush species was also replenished with the same species, *Scirpus validus*. The original iris species, *Iris virginica shrevei*, was satiated with a similar breed, *Iris versicolor*. In addition to the reintroduction of some of the familiar species, a new variety of plant was introduced into the system; *Saururus cernuus*, more commonly known as lizard's tail. Plants belonging to the family of this species were not used in any of the cases examined within the literature review.

Supplementing the wetlands with these five wetland species was a much needed face-lift for the system, as the bare patches and weed-laden areas were beginning to comprise the majority of wetland area. However, the replanting of the cells has two significant drawbacks with regard to the pollutant removal method and capability of the system. First, it is anticipated that the immature plants in the system will need time to fully establish themselves in order to be able to have the capability of promoting the remediation of wastewater to a level as high as that of the fully mature plants within the system. When the wetland cells were originally planted in 2003, it took some time before the plants became fully established, and within that time period, concentration removal capability of the system was found to be weak, although steadily increasing as the plants matured and grew. Because plants have been proven to be significant promoters of treatment (as discussed in the literature review), their lack of performance due to immaturity may be reflected in the quality of the treated wastewater until they become established.

Secondly, the planting scheme itself has changed; a variable that could have caused significant changes in treatment data since replanting. The wetland cells were replenished with just five new species, rather than a combination of the original thirteen. Also, most of the newly introduced plants were not the original species used. This could mean that some original species are or will soon become fully extinct within the wetlands. The literature that was reviewed proved that there were significant changes in treatment capability of a constructed wetland based on the types of plants used.

Throughout the study period, however, it was observed that the wetland plants found in the polishing wetland cell W-3 maintained their vitality for a longer amount of time than the plants found in cells W-1 and W-2. This wetland cell was also observed to have much less loss of wetland plants and fewer invasive species growing with the cell. Although a complete photographic timeline is not available of wetland cell W-3, Figure 7.24 exhibits the cell in the summer of 2005. More details of water quality analysis of Greenfield CW system can be found in Konopka (2007).

Figure 7.24 - Wetland cell W-3

CHAPTER 8

PROJECT EXPERIENCES OF REST AREA WETLAND TREATMENT SYSTEM

Even though constructed wetlands have shown potential for treating wastewater naturally and economically, it should be noted that there are large uncertainties involved in the design, construction and maintenance of wetlands. A great number of variables affect the successful operation of a CW, including size and topography of a wetland, type of treatment structures, arrangement of wetland cells, choice of treatment plants, selection of wetland media, design flow rate, local soil and groundwater features, and climate characteristics. Quantitative relationships among all affecting variables are yet to be understood, and hence more investigation and experience is needed. Through the application of wetland treatment system in the I-70 Greenfield rest area, this chapter provides a summary of the overall experience. It is hoped that this information will help evaluate wetland treatment capabilities, and serve as a useful reference for future implementation of wetlands at rest areas.

8.1 ADEQUACY OF WETLAND SIZE

From the treatment performance shown in Table 7.3, an overall observation of the pollutant reduction rate of the entire system (from ST to AS-4) suggested 65.8% for BOD (430 to 147 mg/l), 78.9% for TSS (175 to 37 mg/l), and 42.1% for NH_3-N (183 to 106 mg/l). Based on the design flow rate as 5,000 gallon/day and surface area at 12,600 ft^2, the BOD_5 mass removal rate is around 47.35 kg/ha/day. Though it may not be directly comparable between different projects, the performance of Greenfield wetland was found similar to what has been reported in previous studies (Sundaravadivel and Vigneswaran, 2001).

As mentioned, one special feature of wastewater generated from highway rest area is its high concentration, and has been a cause of concern for I-70 Greenfield rest area prior to the implementation of wetland project. As notified by the Greenfield wastewater treatment plant, the maximum allowable BOD is 204 mg/l and the exceedance amounts are subject to surcharges. In the case of I-70 Greenfield rest area, the influent concentration (ST in Table 7.3) was around twice the maximum allowance and therefore extra processing fees could be levied. As shown in Table 7.3, the pretreatment provided by wetlands reduced the pollutant concentrations to below this limit, and hence the wetland system would prevent the imposition of a surcharge fee by the City of Greenfield.

Nevertheless, even with reductions in contaminants, the effluent did not meet surface and subsurface discharge regulations (see Table 8.1). In order to achieve on-site discharge for Greenfield rest area, the expected monthly average reductions of 97.7% for BOD (430 to 10 mg/l), 93.1% for TSS (175 to 12 mg/l), and 99% for NH_3-N would be needed. It is highly unlikely that these levels will be attained given the current size of Greenfield wetland, no matter how the development of wetland plants is optimized. Based on the assumption of microbial model (Kadlec and Knight, 1996) under the same operating conditions (i.e., reduction rate of the current wetland is assumed to be a constant), a wetland system about twice the current size is needed to satisfy the TSS requirement, while a four times larger one for satisfying BOD and eight times larger wetland for satisfying ammonia requirements. This estimation is far from what was expected during design steps. It highlights the difficulty in determining the required surface area for wetland wastewater treatment, especially when dealing with high pollutant loads as those generated at highway rest areas. The surface area of wetland should be maximized to the extent possible. The required wetland area should allow for over-design. Most rest areas are located remotely and the availability of increased land area is a possibility.

Table 8.1 - Surface water discharge limitations (Source: Indiana Administrative Code; 327 IAC 5-10-4)

Pollutant	Average Concentrations (mg/L)	
	Monthly	Weekly
$CBOD_5$	10	15
Total Suspended Solids (TSS)	12	18
T. Ammonia, as N		
Summer (May through November)	1.1	1.6
Winter (December through April)	1.6	2.4

8.2 WETLAND TREATMENT SYSTEMS

Compared to conventional plug-flow treatment systems, the Greenfield wetland system adopted two special mechanisms: drain-and-fill parallel wetland cells and recirculation. Because the hydrology of a conventional CW was judged as being inadequate to provide significant primary and secondary treatment to such high strength wastewater, these two mechanisms were brought in to raise the treatment capability. However, they also introduced some extra complexities to the operation and maintenance of the wetland system, and hence their performance deserves examination.

As suggested in many previous studies (Wieder *et al.*, 1989; Behrends *et al.*, 2001; US EPA, 2000), drain-and-fill mechanism for parallel wetland cells can create frequent alternation of aerobic and anaerobic environments in the wetland substrate and therefore expedite the processes of nitrification and denitrification, which play important roles in breaking down NH_3-N. It was expected that the long hydraulic retention time (HRT) required for the nitrogen removal associated with the conventional systems can be efficiently decreased. However, some difficulties were encountered during the operation of Greenfield wetland:

(1) **Control of water levels in the wetland cells**. During different phases of wetland plant development, it is often necessary to maintain the subsurface water level at specific heights to sustain the plants. For instance, sufficient water (nearly full cell) is needed when the wetland plants are newly settled, and during the early growing phase in spring. When the plants become stronger, the water level should be gradually lowered in order to stress the wetland plants and make the root systems grow deeper and wider. However, this cannot be achieved easily for drain-and-fill system. It was especially difficult before the surge tank was installed, since the high variability of wastewater volume combined with drain-and-fill mechanism made the water level unstable. This was perhaps one reason that the wetland plants failed to grow properly and a replanting became necessary.

(2) **Operational and maintenance costs.** One of the biggest advantages of using a wetland system to treat wastewater is its low construction and maintenance costs. Therefore, the design of wetland system should remain simple, preferably drain by gravitational flow with as little mechanical equipments (like pumps) as possible. Though drain-and-fill process may increase the treatment ability of wetlands, it nevertheless raises the operational and maintenance costs. In this aspect, other alternatives should be considered, such as enlarging the area of wetlands system.

Though it has been touted that wetland treatment systems tend to be low-maintenance, the drain-and-fill system however needed constant attention, especially when certain water levels needed to be established. There were occasions that the wetland cells were over-drained and required several days for recovery. However, limited personnel at rest areas made the close monitoring of wetland systems unlikely.

(3) **Drain-and-fill system**. As mentioned in the previous section, the current performance level of Greenfield wetland is not high enough to meet the standards for on-site discharge. This limitation seemed to be more related to the size of wetland, and may not be dramatically improved by using the drain-and-fill mechanism. This mechanism may provide only an added benefit for well-established wetlands of sufficient size.

(4) **Recirculation**. Recirculation was adopted to increase the overall treatment efficiency. Ideally, since part of the effluent was pumped back for re-treatment, the wastewater would get more chance to be treated. This was based on the assumption that wetland cells can always absorb a certain proportion of contaminant from each dosage. However, it should be noted that once the inflow pollutant concentration becomes too high and exceeds the maximum treatment capacity of the wetland cells, recirculation may not provide the anticipated benefits. In this case, the performance of the wetland cells will be controlled by the maximum treatment capability which is more a function of the size of wetland.

In the initial stages of the Greenfield wetland project, the recirculation system also played an important role as a buffer for adjusting high variability of wastewater volume. However, this function was later handled by the surge tank. Though recirculation could improve treatment performance, it involved extra pumping effort and hence expenses for operation and maintenance increased.

(5) Rainfall events. Wetland operations were challenged during days of heavy rainfall. Due to the direct-runoff from precipitation, large amounts of rainfall were often trapped in the wetland cells (in the order of thousands of gallons). This part of the water did not require treatment but its drainage was seriously delayed due to recirculation. After large rainfall events occurred, the circulating pump at LS-2 operated quite frequently to handle this extra load. It would take several days before most of the precipitation was drained out from the system, but the next rainfall event would trigger the same effects. Like the drain-and-fill mechanism, recirculation would likely be useful if the drain-and- fill mechanism did provide enough oxygen for treatment, and may provide added benefit to a well-established wetland.

Another factor that should be considered when designing CW is the role of rainfall, especially when the wetland serves as the pretreatment system. Though precipitation can help dilute the wastewater and lower the contaminant concentration immediately, it raises the total effluent volume and hence increases the sewage bill from local treatment plant (if calculated by total volume). While it is hard to prevent direct rainfall from entering wetland cells, some storm water ditches could be built around the system to intercept the direct-runoff from surrounding areas and help lower the amount of storm water entering the system. Nevertheless, if effluent volume is not a concern or the wetland treatment system aims for on-site discharge, rainfall can be a help to the wetland plants and storm water can also be treated through the wetland system.

Based on the operating experience of Greenfield wetlands, it is suggested to keep the system simple, and adopt as few lift stations as possible. Considering the general features of highway rest areas (low cost for lands and high cost for maintenance), a simpler large plug-flow system may work better than a sophisticated recirculational drain-and-fill system. Except for facilities such as surge tank and initial lift station being required to control dosing and stabilization of water levels in wetland cells, most of the system should be designed for gravitational flow. Some cost-efficiency issues will be discussed in later sections.

8.3 UPKEEP OF WETLAND PLANTS

Wetland plants need a stable environment and a continuous water supply, as offered in natural wetlands. While natural wetlands are able to absorb various kinds of contaminants, constructed wetlands outfitted with one or more types of wetland plants are expected to create similar environments. Nevertheless, it should be noted that natural wetlands are already established and maintain a sensitive balance between topography, weather, soil type, ground water level, vegetation and other affecting variables. Once any condition is altered and the balance is shifted, the wetland will begin to evolve or gradually disappear. While constructed wetlands aim to establish long-term and self-sustained systems, it is possible that the balance cannot be achieved within a short time frame (the wetlands are either too dry or wet) and may cause the wetland plants to vanish eventually.

Therefore, it is necessary to monitor the conditions of constructed wetlands to ensure that they operate as designed. Periodic visits should be made to examine the general status of wetland plants. Once it is judged that the influent is insufficient or too much for the health of the plants, the water levels within wetland cells should be adjusted accordingly through dosing tanks or level-controlling outlet structures. If necessary, fertilizers and micronutrients can be added to help promote healthy plant growth. For larger wetlands, monitoring is required to observe if plants grow well uniformly over the entire cell. If plant growth is stagnant in some regions, the water level should be adjusted accordingly. Stagnant plant regions may also be created if portions of the wetland are short-circuited. Feeding part of the influent directly to such stagnant zones may be needed to alleviate this situation.

Management of the water level in the wetland cells is especially important during the early growth period of vegetation, when the wetland plants are vulnerable and cannot endure sudden changes. As mentioned earlier, water levels can be gradually reduced (rate should not be greater than the growing rate of roots) to promote root penetration and establish root density. Flooding conditions should be avoided until the plants grow high enough to have leaves protruding above the water level. As observed in the Greenfield wetland, there was a noticeable "start up" period, in which the treatment performance was weak at the beginning. Nevertheless, once the wetland plants were established, a sustained level of performance was observed.

For selection of suitable treatment agents, wetland plants with robust biomass production are favored. Denser root systems can foster a better metabolizing habitat for bacteria within the root zone. Treatment plants that can be found locally would be preferable, since these plants have already been established through biological competition. Winter is the most limiting season, and wetland plants with the least reduction in performance during winter are the best. Besides, wetland plants that are perennial, establish quickly, and process a lot of energy while out-competing other invasive species will thrive in a constructed wetland system with increased nutrient levels in influent streams.

As for plant orientation among mixed cultures of wetland plants, it was suggested from previous studies that orienting different species of plants in a specific and separate arrangement within the same wetland cell can prevent problems that inhibit productivity. Taller or larger plants pose problems to smaller plants in that they shade the lower plants, thus causing plant stress. Plants with larger or deeper root systems also affect plants with smaller or shallower root systems in that deeper or larger root systems take away water and nutrients from plants that have shallower and smaller root systems. Additionally, species with shallow root systems have to compete with invasive plant species. Within a constructed wetland cell, these issues are important because competition between plants can ultimately lead to the extinction of certain wetland plants within wetland cells as was noticed at the Greenfield rest area. Species that are planted and then lost due to these reasons are not an effective use of resources.

8.4 APPLICABILITY OF BIOFIELD FOR SUBSURFACE DISCHARGE

As shown in Figure 3.3, a biofield (composed of sand mound with the top seeded with prairie grass) was built following LS-3 to test the applicability of on-site subsurface disposal. It was expected that the biofield would increase denitrification of wastewater, and finally dispose the treated effluent by evapotranspiration and infiltration to the subsoil.

If the ultimate goal is to achieve on-site discharge, the biofield will play an important role. However, some problems were encountered during the operation of Greenfield wetland, the most serious one being the very low soil infiltration capacity (hydraulic conductivity *K* (cm/hr) being small). An on-site infiltration test was performed and it showed that the local soil was nearly impermeable, therefore affecting the drainage ability of biofield. In addition, the high ground water level imposed further limitations when large amounts of treated water needed to be discharged.

In order to investigate the general applicability of biofields for Indiana rest areas, the State Soil Graphical (STATGO) Data Base from United States Department of Agriculture was consulted. By overlaying the existing locations of Indiana interstate rest areas with the STATGO soil layers, the compositions of soil properties at each rest area were found. The average hydraulic conductivity *K* was calculated and listed in Table 8.2. The locations of Indiana interstate rest areas were plotted in Figure 8.1 along with the corresponding *K* values. It should be first stated that the soil information provided by

Table 8.2 - Average hydraulic conductivity *K* (cm/hr) estimated from STATGO dataset for all interstate rest areas in Indiana (I70-107 is the Greenfield rest area).

NAME	LAT	LON	*K* (cm/hr)	NAME	LAT	LON	*K* (cm/hr)
I64-007(E)	38.1950	-87.8596	0.65	I70-107(E)	39.8243	-85.7039	0.43
I64-058(E)	38.1950	-86.9486	0.65	I70-107(W)	39.8266	-85.7039	0.43
I64-058(W)	38.1976	-86.9481	0.65	I70-144(E)	39.8586	-85.0232	0.43
I64-115(W)	38.2773	-85.9636	0.57	I70-144(W)	39.8603	-85.0233	0.43
I65-022(N)	38.5851	-85.7767	0.62	I74-001(E)	40.1164	-87.5049	0.63
I65-022(S)	38.5859	-85.7808	0.62	I74-023(E)	40.1134	-87.1118	0.65
I65-073(N)	39.2602	-85.9521	0.53	I74-023(W)	40.1151	-87.1117	0.65
I65-073(S)	39.2767	-85.9569	0.48	I74-057(E)	39.8995	-86.5550	0.43
I65-148(N)	40.1578	-86.5388	0.53	I74-057(W)	39.9015	-86.5541	0.43
I65-150(S)	40.1722	-86.5522	0.43	I74-152(E)	39.2905	-85.1760	0.65
I65-196(N)	40.6992	-87.0627	0.32	I74-152(W)	39.2892	-85.1686	0.65
I65-196(S)	40.6984	-87.0646	2.40	I80/90-022(E)	41.5869	-87.2176	3.77
I65-231(N)	41.1652	-87.2710	3.77	I80/90-022(W)	41.5888	-87.2165	2.40
I65-231(S)	41.1666	-87.2749	3.77	I80/90-056(E)	41.7058	-86.6212	0.56
I69-050(N)	40.3519	-85.5575	0.43	I80/90-056(W)	41.7070	-86.6234	0.56
I69-050(S)	40.3604	-85.5600	0.46	I80/90-090(E)	41.7312	-86.0048	1.07
I69-089(N)	40.8681	-85.3435	0.46	I80/90-090(W)	41.7333	-86.0051	3.77
I69-093(S)	40.9143	-85.3284	0.50	I80/90-126(E)	41.7450	-85.3293	0.98
I69-144(S)	41.5806	-85.0602	0.50	I80/90-126(W)	41.7470	-85.3286	0.98
I70-001(E)	39.4362	-87.5282	0.55	I80/90-146(E)	41.7251	-84.9679	0.56
I70-065(E)	39.6517	-86.3967	0.48	I80/90-146(W)	41.7266	-84.9657	0.56
I70-065(W)	39.6540	-86.4006	0.48	I94-043(W)	41.7352	-86.7931	0.46

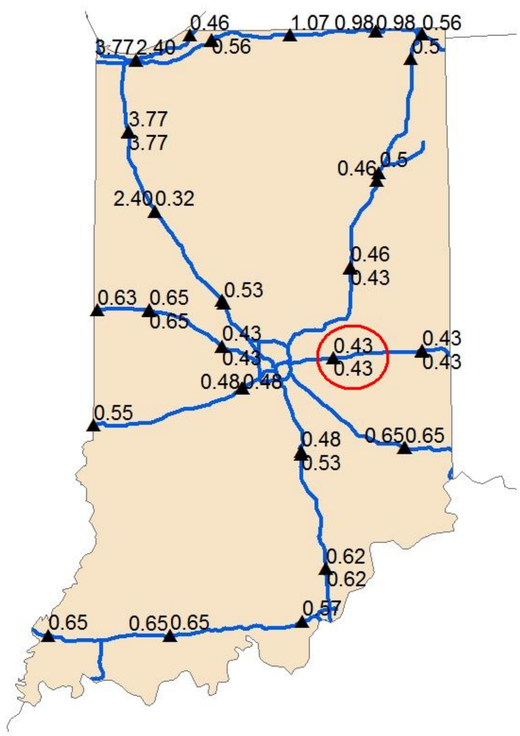


Figure 8.1 - Rest areas in Indiana and the corresponding average values of conductivity *K* (cm/hr)

STATGO has a coarse spatial resolution, and hence it merely gives the areal average information implying that large local variations may exist. For instance, the *K* value of Greenfield wetland estimated from STATGO was much greater than the one obtained from an on-site experiment. Nevertheless, Table 8.2 gives a relative indication of the general soil properties for all Indiana rest areas. The Greenfield rest area is at a location where soils have the least conductivity in the state. When evaluating a potential site for a biofield, locations with high hydraulic conductivity should be preferred.

Besides the problem of low conductivity, it was also found that biofield had limited treating ability compared to wetlands (as shown in Table 7.3). This was to be expected since the current biofield is simply a deep sand mound covered with prairie grass. Unless the wetland is composed of appropriate media, the biofield should only receive low-strength wastewater, which can be essentially evapotranspired over the biofield surface area.

8.5 MAINTENANCE OF THE SYSTEM

While constructed wetlands are touted as low less maintenance systems compared to other conventional wastewater treatment approaches, they do require some maintenance especially with the unique challenges posed by wetlands. In fact, proper maintenance of the wetland facilities is a key factor for achieving optimal performance. If stationed on-site personnel are unavailable, regular visits should be made. The major objectives of maintenance include:

(1) **Examining the vegetation cover.** As mentioned earlier, the health of the plants is an important factor in wetland treatment. Since constructed wetlands are a man-made environment, they should be carefully monitored to ensure that the plants grow as planned. This part of maintenance is particularly important when plants are newly established or during each spring season. Great care needs to be exercised until the desired vegetation is fully established. Appropriate preventative measures are needed if some locally invasive species (weeds or other undesirable plants) intrude the wetland and threaten the existence of selected treatment plants. If certain diseased wetland plants are struggling to survive, other alternatives should be considered.

(2) **Adjusting the water levels in wetland cells.** Based on the conditions of wetland plants and weather, the amount of effluent and the water levels in wetland cells should be adjusted accordingly. Dramatic changes of water supply to plants should be avoided. The water level can be lowered gradually to promote the development of root zones. Flooding should also be avoided for subsurface constructed wetlands. If the wetland is located on lower ground, rainfall-induced direct-runoff from nearby regions can be a threat to the wetland system and hence a drainage system may be required to keep off-site water out of the system.

(3) **Maintenance of wetland facilities.** Wetland equipment, including surge and septic tanks, pumps, lift stations, flow meters, and inlet and outlet structures need to be checked during regular visits. It is important to keep wetland components functioning properly for optimal performance. Early warning mechanisms can be developed to deal with problems before it is too late. Due to undecomposable trash and materials, it was reported that the filters in the inlet of wetlands (septic tanks) were usually clogged and needed to be cleaned every month. The other problem is lightning, which has caused breakdown of the monitoring equipments at least twice for the Greenfield wetland. Some protection mechanisms can be considered to prevent such incidents.

Clearly, proper maintenance is required for the success of constructed wetlands. However, this may be a major limitation for most highway rest areas that lack sufficient resources. Thus, the preference for a simple treatment system, rather than a complicated one, should be a goal of wetland design. The drain-and-fill and recirculation mechanisms of the Greenfield wetland systems required a combination of a variety of facilities (one surge tank, two septic tanks, three wetland cells, four pumps and lift stations, four automatic samplers, four magnetic and three open channel flow meters, and the SCADA system), which contribute to increased maintenance costs. One might consider utilizing the advantages of rest areas at remote locations (low land cost) to construct a simpler but larger wetland system, which should be able to reduce the demand for maintenance.

8.6 COST-EFFICIENCY OF TREATMENT WETLAND

As mentioned earlier, most highway rest areas produce high-strength wastewater and are located remotely. In the case of I-70 Greenfield rest area, a long sewage line (more than three miles) with residence time in the order of three to four days was used to transport the effluent to the Greenfield wastewater treatment plant. Based on its sewage rates and charges (http://www.greenfieldin.org/egov/docs/1152277800_30639.pdf), the wastewater treatment fee is estimated to be around $12,000 per year. However, due to the high strength and bad odor of wastewater, it may be subject to further surcharges. From the water quality data collected from the surge tank (listed in Table 7.3), the potential surcharge is estimated and listed in Table 8.3. The estimate is based on the weight of pollutant that exceeds the estimated limits (204 mg/L for BOD, 240 mg/L for TSS, and 30 mg/L for NH_3-N). For an average discharge of 10,000 gallons per day, the resulting surcharge of Greenfield rest area will be approximately $4,000 per year (not including the regular treatment expenses). Nevertheless, it should be noted that the actual surcharge would likely be higher since the wastewater quality is expected to be worse when it arrives at the treatment plant.

Table 8.3 - The potential wastewater treatment surcharge of the I-70 Greenfield rest area

	Greenfield effluent (mg/L)	Surcharge cutoff (mg/L)	Rate surcharge ($/lb)	Annual cost ($) for 10,000 GPD average flow
BOD	430	204	0.25	1,720
TSS	175	240	0.25	N/A
NH_3-N	183	30	0.5	2,329
			Annual total surcharge	4,049

To lower the contaminant concentration and test the applicability of other on-site pretreatment choices, it was decided to build a constructed wetland system in the Greenfield rest area. The initial evaluation of several construction options proposed by RQAW in 2000 is listed in Table 8.4. Three scenarios were compared, including paying surcharge, constructing treatment wetlands, and adopting biomechanical pretreatment system. The on-site conventional treatment system (Option 3) was found to be the most expensive choice. However, for those highway rest areas that are located far away from local treatment plants, perhaps treatment plants are a common option. By comparing Option 2 with Option 3, it can be observed that even with a more sophisticated design, wetland system is still cheaper than the conventional approach. The construction and maintenance costs of the wetland could be lowered if a simpler system is adopted. Based on the relatively low cost of Option 1 plus surcharge, it may be stated that paying the surcharge would be an economical choice. Nevertheless, another potential cost should be considered. Since extended sewage lines must be built to help transport wastewater, the construction and following overhaul costs would be quite expensive. If on-site wetland treatment can be achieved, not only the surcharge but the total wastewater treatment costs of local plants can also be saved. To test the applicability of wetland, Option 2b was eventually selected.

Table 8.4 - Construction costs of Greenfield wetland treatment system for different treatment options

	Capital costs	Annual O/M
Initial estimation (email from RQAW, 2000)		
Option 1: Paying surcharge and installing ozonator	$30,000	$3,000
Option 2a: Wetland pretreatment with no biofield	$222,000	$1,875
Option 2b: Wetland with biofield	$257,000	$510
Option 3: Biomechanical pretreatment system	> $270,000	$20,000
Actual construction costs at 2003		
Wetland with biofield (no surge tank was installed at this time)	$428,717	$5,623 [1]

[1] Only the cost for sludge cleaning was included.

The construction cost estimates provided in Table 8.3 were not realized. The final construction cost turned to be $428,717 (included in Table 8.4) but it was later increased due to change of design. Maintenance fee was also found to be higher than expected. Without considering the internal labor costs and equipment expenses for fixing broken instruments, the sludge cleaning from the septic tank was performed nearly monthly, and it cost around $5,600 per year. Other supplementary expenses included installation of surge tanks, generators and SCADA systems, fixing of pumps, flow meters and other facilities due to lightning damage, regular cleaning of septic tanks, and costs for replanting. The final cost was estimated to be around one million dollars overall.

To help illustrate and compare the costs, Figure 8.2 is prepared based on the information listed in Tables 8.3 and 8.4. Assuming that the effluent of Greenfield rest area will be sent to the local treatment plant, Fig. 8.2(a) compares the pretreatment costs of using wetland versus surcharge for the following ten years. It is clear that apart from the high initial construction cost, the annual O/M expense of wetland is greater than the surcharge and hence using wetland for pretreatment is not an economic choice. Fig. 8.2(b) compares the total costs for on-site versus centralized treatments, in which the annual cost of wetland, biomechanical system, and the total centralized wastewater treatment fee (basic plus surcharge) were plotted for the next ten years. It should be noted that since the current size of wetland is insufficient in achieving the on-site disposal standard, the actual capital cost of wetland would be lifted. Nevertheless, because the annual O/M cost of conventional on-site treatment facility is much higher, wetland could eventually be an economic choice, but it will be in the order of more than ten years. The centralized treatment is again the most economic choice, and it implies that wetland may not be suitable for highway rest areas when centralized collection is available.

From the cost aspect, the most important lesson obtained from Greenfield wetland project is to keep the wetland systems as simple as possible. The flow to and from wetland cells should be driven by gravity with minimal mechanical equipments. Since the availability of land may not be an issue for rest areas, it may be preferable to opt for a large and simple wetland system instead of a small and sophisticated one.

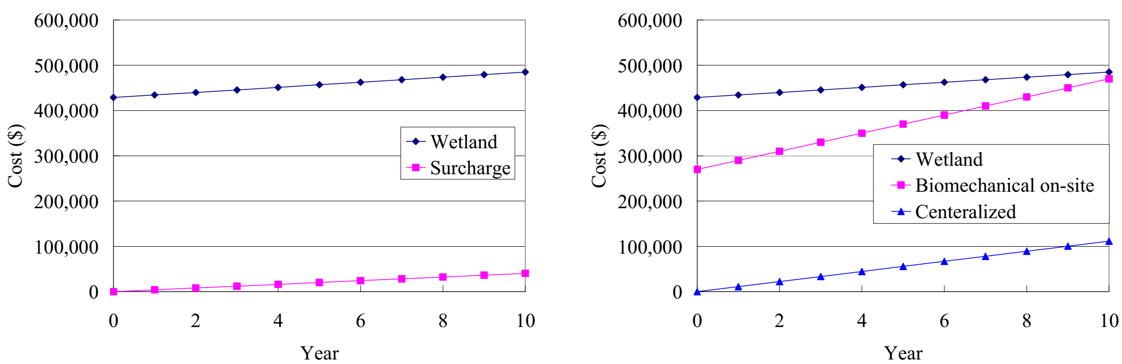


Figure 8.2 - Cost analysis of Greenfield wetland: (a) Using wetland as the pretreatment system versus paying surcharge, and (b) Using wetland or biomechanical system to perform on-site treatment versus centralized approach

CHAPTER 9

GUIDELINES FOR HIGHWAY REST AREA WASTEWATER TREATMENT WETLANDS

The design of typical treatment wetlands has been described in many studies (e.g., Kadlec and Knight, 1996). However, due to many uncertainties involved, most of the wetland mechanisms cannot be described quantitatively. The desired system usually cannot be designed precisely to match at-site requirements, and hence some flexibility needs to be built into the design. In many cases, previous experience from projects with similar objectives, wastewater qualities, site properties, geographic location, and climate conditions provide the most important references. For the use of treatment wetlands in highway rest areas, such experience is not available. Owing to the special challenges of rest area wastewater treatment (remote location, high strength of wastewater, high variability in wastewater flow, and limited personnel), the design of wetland treatment requires special consideration. The following guidelines of wetland treatment system for highway rest areas are provided based on the experience from the Greenfield wetland project. Some considerations which are crucial to rest areas are highlighted.

9.1 SIZING OF WETLAND

Wetlands treat wastewaters through biological, physical, and chemical processes that mainly correlate to the surface area of the bed material. Therefore, the first step in designing a wetland is to determine its size to meet the discharge requirements. Without site-specific information, basic sizing can be performed based on microbial growth model (Sundaravadivel and Vigneswaran, 2001). Conventionally, a horizontal plug flow model has been adopted, and it is assumed that microorganisms in the wetlands follow first order reaction kinetics (as shown in Eqs. 2.9 and 2.10). Taking Greenfield wetland as an example, to satisfy the BOD standard for on-site disposal with C_0 = 430 mg/L, C_t = 10 mg/L and $T = 27^\circ\mathrm{C}$, the theoretical retention time would be 2.23 days. After the required retention time has been estimated, the details of wetland cells can be further designed to achieve the desired flow rate (Q). For the plug-flow system, HRT can be related to Q by (Chan *et al.*, 2005):

$$\text{HRT} = \frac{V_{sys}\eta}{Q} \tag{9.1}$$

where V_{sys} is the nominal volume of the system, η the porosity of the substrates, and Q the flow rate. For horizontal subsurface wetland cells, the depth d is typically less than 2 ft. With known design flow rate Q and porosity η, the required wetland volume V_{sys} can be estimated, and the required wetland surface area can be computed based on the given depth d and the geometry of cells.

However, it should be noted that there are large uncertainties involved in such an estimation, and hence it merely provides a preliminary estimator of retention time. If empirical data from similar wetlands or pilot studies are available, they can provide a more reliable estimation. This was found to be especially important for application in rest areas since the pretreated wastewater was at much higher contaminant levels compared to other studies (the computed retention time may not be sufficient and should allow for over-design). Assuming the cost of land is relatively cheap near most rest areas, it is suggested that enlarging the size of wetland would ensure a better performance. For the Greenfield wetland system, based on a design flow rate as 5,000 gallon/day and surface area at 11,000 ft^2, it reduced average BOD from 430 to 147 mg/L (65.81%) which equaled 54.27 kg/ha/day. It can be used as a reference for future similar systems.

9.2 SITE SELECTION AND ARRANGEMENT OF WETLAND CELLS

Though wastewater treatment wetlands can be classified into surface and subsurface types, the focus will be on the subsurface wetlands in the following discussion. Subsurface constructed wetlands are less likely to have odor problems. Depending on the proposed size of wetland, several types of wetland arrangements can be considered. Typical selections include a single cell, series cells, parallel cells, or combination of series and parallel cells (like the system used in Greenfield rest area). Given a total area, the wetland cells should be designed to provide the longest traveling distance (serpentine type). The major consideration is to lower the chance of short-circulating within the substrate and increase the overall hydraulic retention time. While series and parallel cells can provide flexible operations of wetland treatment and have a lower potential to short-circuiting compared to a large single cell, they nevertheless complicate the system and increase both the construction cost and maintenance need. If a large single cell is adopted, the step feed system (influent being divided into several parts and sent to the cell uniformly) can be used to mitigate potential short-circuiting problems.

For site selection, slope, soil infiltration capability and local ground water level are factors of concern. As discussed in Chapter 8, gravitational flow is preferred based on the experience of Greenfield project and therefore sufficient wetland slope is desirable. If the wetland system aims to achieve subsurface on-site disposal through biofields, the soil conductivity should be tested at potential locations, and places with clay or other low-permeability soil textures should be avoided. Site locations with high subsurface water levels should not be favored, because if the ground water table is higher than the bottom of wetland cells, the lateral water pressure may result in water pockets under cell liners and could cause leakage to and from the wetland cells.

9.3 WETLAND MEDIA

Based on the content of media, the wetland systems can be mainly classified into two types: soil-based or gravel-based. While soil is the common media for natural wetlands and is cheaper for construction comparing to gravel, it may not be a suitable choice for constructed wetland. Clogging has been reported to be a serious and common problem for soil-based wetland systems, in which the solid particles rapidly obstruct the passages between media and caused the wastewater to overflow. On the contrary, gravel-based media promotes filtration and settling of suspended particles, and it also provides sufficient surface area for the attachment of microorganisms thereby facilitating treatment. During the operation of Greenfield wetland system, no obvious problem was reported due to the use of gravel-based media.

The depth of wetland media are typically reported to be less than 0.6 m for horizontal subsurface wetlands (Sundaravadivel and Vigneswaran, 2001). In case of available land being a limiting factor, one may consider deepening the depth of wetland cells to sustain a desired volume, such as decided for Greenfield wetland. Since linings around wetland cells are needed to prevent contamination of groundwater, it should be noted that the wetland media cannot be too shallow or otherwise the linings would be gradually penetrated by the roots of wetland plants.

9.4 WETLAND PLANTS

Wetland plants play a central role in wastewater treatment, and it is recognized that plants with high biomass production can provide better treatment. A study relating effect of ammonia concentration to biomass production of five common wetland plants concluded that species with greater biomass could remove more nutrient ammonia from influent wastewaters than those with less biomass (Hill *et al.*, 1997). However, biomass production is not the only criterion in plant selection. For instance, native species are preferable for wetland systems since they have higher chances of long-term survival. Overall, potential wetland plants should possess as many of the following features as possible:

- Plants are among the native species and can be found locally.
- Plants with high growth rate and long annual growing period.
- Plants with widely spread root systems.
- Plants with short start-up period.
- Plants capable of enduring large variability of weather and water supply.
- Plants that are least affected in performance during winter.
- Plants capable of competing with invasive species.
- Plants that are cheap for planting and maintaining.
- Plants that are compatible to other selected species.
- Plants causing no impact to the local ecosystem.

Spring has been reported to be the most appropriate season for planting as it allows sufficient time for plants to grow and survive the first winter. Several approaches of planting can be used, including the use of seeds, propagated seedlings, transplantations, or rhizomes. Though the use of seeds could be the cheapest choice, it often takes a long time for plants to develop and hence is not recommended. On the contrary, direct planting of propagated seedlings is the most common and cost-effective selection (Surrency, 1993). It should be noted that it may take two to three growing seasons for the wetland plants to be well-established and reach their full treatment potential. Close monitoring of wetland plants in the early development phase is necessary. Wetland plants should be adjusted (i.e., replanting, reseeding, and *etc*.) based on their actual growing situation. It is expected that under a stable environment, the development of plants in constructed wetlands will gradually reach equilibrium.

9.5 OTHER WETLAND FACILITIES

In order to keep the wetland systems functional, additional facilities such as surge and septic tanks, pumps and lift stations, flow controlling equipment, and monitoring instruments are required. Nevertheless, these facilities need regular maintenance and thus the operating costs rise. With limited manpower, equipment that provides better efficiency and require less attention is preferred.

Based on the experience of Greenfield wetland, a surge tank is recommended as the dosing device to the entire wetland system. To lessen the effect of high variability of rest area wastewater and retain a stable supply of influent into wetland cells, the surge tank can be used as a buffer zone to temporarily store the wastewater. The size of surge tank should be large enough to contain the peak volume of wastewater. Following the surge tank, the septic tanks can provide primary treatment and are useful in settling the undecomposable solids and helping prevent short-circuiting within wetland media. Depending on the quality of wastewater, the septic tanks might require frequent cleaning. For the average influent as 5,000 gallon/day, the 10,000-gallon septic tanks in Greenfield wetland system required monthly cleaning.

Pumps and lift stations are needed when the available elevation head is not sufficient to maintain desired flows. Low and high water level alarms should be placed in the lift stations to prevent the breakdown of pumps and the back- or over-flow of wastewater. The pumps can be triggered automatically by level sensors or by operating on a given schedule. Multiple pumps instead of a single pump should be adopted to allow flexibility in maintenance and operation. Emergency backup power might be required for continuous operation. Monitoring instruments can be installed to help understand the wetland performance and be used to control wetland operation.

9.6 CHECKLIST FOR POTENTIAL SITE EVALUATION

For constructing treatment wetlands in highway rest areas, a checklist for evaluating a potential site is organized below. The following items should be considered to ensure good performance of a wetland system.

Most important factors:

- Are the magnitude and variation of wastewater flowrates known?
- Is there sufficient land available for placement of wetland cells?
- Can gravitational flow be achieved in most parts of the system?
- Is sufficient man-power available to monitor and maintain the system?

Important factors:

- What is the distance to the nearby conventional treatment plant?
- What level of treatment (pre- or final-) should the wetland provide?
- How many pumps and lift stations will be needed for raising wastewater?

Less important factors:

- Have the soil characteristics of site been investigated?
- Is biofield an option for on-site discharge?
- Are there alternative treatments available?
- What is the severity of winters and how will the wetland plants be affected?
- Are there any suitable native plants to use in wetland?

CHAPTER 10

CONCLUSIONS AND SUGGESTIONS FOR FUTURE IMPLEMENTATION

10.1 CONCLUSIONS ABOUT THE OVERALL PERFORMANCE OF THE I-70 GREENFIELD WETLAND WASTEWATER TREATMENT SYSTEM

In an efforts address the wastewater treatment problems in highway rest areas, a constructed wetland system was built in the interstate I-70 Greenfield rest area to investigate the applicability of wastewater treatment using wetlands. The following conclusions are presented based on the overall project experience.

1. Based on the design flow rate as 5,000 gallon/day, the 11,000 ft^2 Greenfield wetland was able to reduce the average BOD from 430 to 147 mg/L (65.81%) which equated to 54.27 kg/ha/day. This performance was found similar to what has been reported in previous studies. The Greenfield wetland system provided sufficient pretreatment so that wastewater could be discharged to the local treatment plant without having to incur any surcharges. However, the wetland did not achieve the standards for on-site discharge. The wetland size was too small to meet this goal.

2. A cyclic draw and fill mechanism, intended to improve the wastewater treatment process within a wetland, did not prove to be a significant catalyst of treatment in the subsurface constructed wetland system. It resulted in difficulties to adjust the water levels in wetland cells. Subsequently, the recirculation mechanism did not show impressive improvements either. It was found that the storm water was usually trapped in the recirculation system and it took an extended time to drain. While these two mechanisms may help improve the treating performance of wetlands, thus also raises the maintenance needs and may not be cost-effective.

3. Plants play a significant role within wetlands, and are essential to the desired functionality of the wetland system for the treatment of effluent from a highway rest area. The treatment efficacy closely correlates to plant health. As wetland plants became increasingly unhealthy, the quality of wastewater treatment also deteriorated.

A noticeable "start up" period of wetland plants for wastewater treatment was observed in the Greenfield wetland system. Two to three growing seasons may be needed for wetland plants to be fully-established. To promote the development of root systems, the water levels within wetland cells may be gradually lowered to stress the plants during the early growing season.

4. If a biofield is to be adopted as the final receptor for wetland effluent and release for subsurface discharge, the local soil must have sufficient infiltration capability (large hydraulic conductivity). By overlaying the STATGO dataset with all interstates in Indiana, the average conductivity was computed for each rest area and it was provided as a reference for the evaluation of other possible wetland sites. It should be noted that the biofield (a sand mound) does not provide any effective treatment and has only evapotranspiration lose benefits.

5. Though wetlands are touted as requiring less maintenance than the other conventional treatment approaches, it does not mean that they are maintenance-free. In fact, necessary maintenance is the key factor for ensuring desired performance from wetlands, especially for rest areas. Therefore, the wetland systems used in highway rest areas should be designed to be simple and require minimal maintenance to keep costs to a minimum.

10.2 SUGGESTIONS FOR FUTURE IMPLEMENTATION

Compared to conventional wastewater treatment approaches, wetlands are cheaper, more natural, and require less maintenance. It is a promising method for remote locations which do not have easy access to a centralized treatment network. While the size of wetland is a major factor affecting its treating capability, it should pose less of a problem for remote areas where the cost of land is relatively cheap. However, in order to ensure good performance of treatment wetlands, the system must be designed properly and sufficient maintenance would be required.

While there are various mechanisms which can help improve the treatment capability, the rule of thumb of wetland design is to keep the system simple, requiring as little maintenance as possible. Special mechanisms such as drain-and-fill and recirculation require extra equipment and attention, and may not be effective unless sufficient manpower is available. Regular visits to the wetlands are required to ensure that the system operates smoothly. The ultimate goal of wetland maintenance is to establish a well-developed and self-sustainable treatment environment, in which the system can provide long-term treatment over a life-time. Constructed wetlands may be a potential alternative for on-site wastewater treatment for highway rest areas, and may be worthy of consideration where site conditions are favorable.

10.3 CONCLUDING THE PROJECT

As discussed above, several important lessons were learned over the course of this project. The following future steps are recommended:

1. The research equipment that is not necessary for day to day operation of the wetland may be deployed for other uses.

2. The waste stream from only the south side should be fed into the wetland system.

3. The system should be tried for another year with minimal maintenance. If the cost of cleaning the septic tanks, upkeep of wetland vegetation, and operation of pumps proves to be very expensive, then the wetland system may be closed down, with the entire wastewater being directed to the city sewer.

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APPENDIX A. CASE STUDY

In addition to the literature that has been reviewed, a case study was performed during the 2004 growing season on a subsurface constructed wetland. The case study examined the removal capabilities of a wetland system in France Park, a large public outdoor recreational facility, and to examine the plants and planting scheme. Included in its many acres are trails, a swimming lake with fishing areas, camping areas, and a subsurface constructed wetland. France Park is located in North Central Indiana on US Highway 24, about 4 miles west of Logansport in Cass County, Indiana. France Park's constructed wetlands were installed in the summer of 1999 to improve the failing septic systems throughout the park. The system was designed by J.F. New & Associates and constructed by Leo Brown Construction. The effluent leaving the system is discharged into a biofield covered by prairie grass.

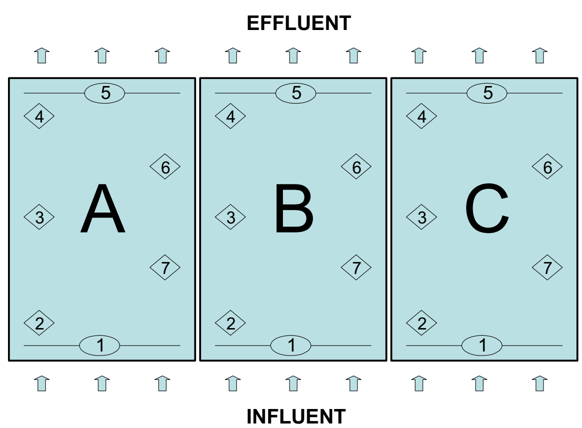

Figure A.1 - Cell configuration with identification scheme

The cell configurations seen in Figure A.1 are not to scale. There are three separate cells, each 106 feet long by 52 feet wide with a depth of 2 feet. Each cell has a separate influent and effluent manifold with separate flow adjustment valves. The media used in the wetlands includes coarse and fine gravel as well as 14 wetland plant species (Table A.1). The wetland cells were photographed extensively to help draft observations. Figure A.2 and Figure A.3 show the differences in plant quality and quantity within two of the three wetland cells at France Park. The wetland plants were oriented in a specific way in each wetland cell. A modified photograph of the original blueprint for one of the cells shows that the influent half of the area was planted with species of *Carex* (Figure A.4). The effluent half of the cells was planted with species of *Scirpus*.

Figure A.2 - Cell "B" influent side.

Figure A.3 - Cell "A" effluent side.

Table A.1 - Plants selected for a constructed wetland system at France Park; Logansport, Indiana.

Scientific Name	Common Name
Asclepias incarnata	Swamp Milkweed
Calla Palustris	Water Arum
Iris pseudacorus	Tall Yellow Iris
Iris virginica shrevei	Blue Flag Iris
Lobelia cardinalis	Cardinal Flower
Lobelia siphilitica	Great Blue Lobelia
Sagittaria latifolia	Common Arrowhead
Carex comosa	Bristly Sedge
Carex bebbi	Bebb's Oval Sedge
Carex vulpinoidea	Brown Fox Sedge
Carex tribuloides	Awl Fruited Sedge
Carex hystericina	Porcupine Sedge
Scirpus fluviatilis	River Bulrush
Scirpus validus creber	Great Bulrush(softstem)

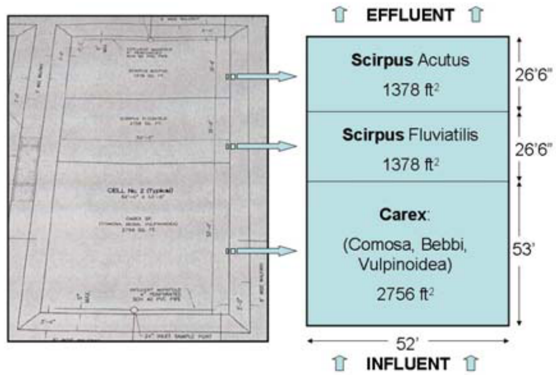

Figure A.4 - Plant selection and planting orientation for a wetland cell at France Park; Logansport, Indiana.

OBSERVATIONS

The site did not appear to be visited regularly and the media was not controlled in the cells. Vegetation quality and quantity throughout each cell varied greatly. In some areas, there was large growth with plants that appeared to be very healthy. Areas with medium-small and small plants were observed as well as large areas (particularly near the latter region of the wetland) that no longer contained wetland plants, only gravel. Figure A.5 shows a general plant distribution for each cell.

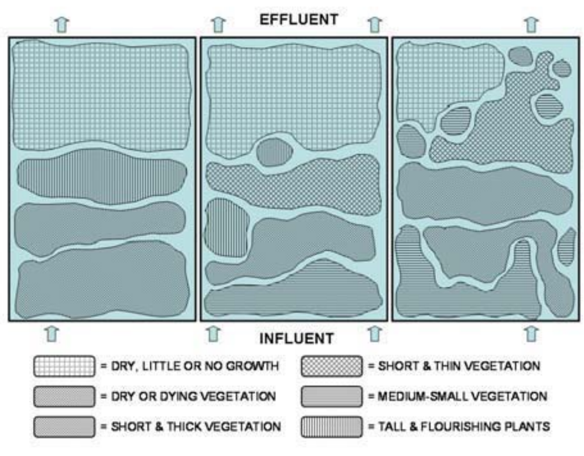

Figure A.5 - Observed vegetation patterns within the wetland cells at France Park.

In general, there was not a wide variety of species observed and many invasive species were noticed Quantity and quality of plants increased as attention was focused from cell

‘A’ to cell ‘C’ (see identification scheme in Fig. A.1).

Cell ‘A’ contained mostly four categories of media. Nearest the influent area was short but thick vegetation with some grasses. Moving towards the effluent side, the plants then appeared very dry. Following that patch was an area of extremely tall plants that stretched across the entire cell. Taking up nearly the last half of cell ‘A’ was dry gravel with very few small grasses growing amid the rocks.

Cell ‘B’ contained more variety than cell ‘A’. Nearest the influent region was some medium-small vegetation followed by some short, thick vegetation. The large patch of extremely tall plants was not present. There were, however, two small patches of plants clearly taller than the rest of the media in cell ‘B’. The center of the cell contained a lot of short but thin plants. The back half of the cell again contained mostly gravel with very few plants growing.

Cell ‘C’ showed the largest variety in media arrangement. Near the influent area and continuing up the left side of the cell were mostly medium-small plants. Closer to the right side was more short and thick vegetation. The center of the cell contained a lot of dry or dying vegetation that was still rather thick. Contrary to the pattern taken by cells ‘A’ and ‘B’, the latter portion near the effluent region of cell ‘C’ contained a much smaller dry patch and had many areas of tall or flourishing growth. There was also an area beginning near the center of the cell and extended into the back end containing short but thin vegetation.

DATA COLLECTION PROCEDURE

In order to analyze the effectiveness of the constructed wetlands and to gain an understanding of wetland performance, samples of the water taken from various points in each cell were analyzed. Wetland plants (non-invasive) were also dug out to observe the root structure and depth.

The identification scheme seen in Fig. A.1 was used to systematically take pictures of the media (gravel) as holes were dug to observe the content and color of the gravel or water. For each cell, location 1 denotes the location of the influent manifold valve and location 5 denotes the location of the effluent manifold valve. Both positions in each cell are located above ground level and there is no gravel surrounding either valve.

To maintain consistency in data collection, the following procedure was used in each wetland cell:

Water:

The manifold covers in locations 1 and 5 were removed and pictures were taken of the water. A sample of water was taken (about 500 mL) from each manifold before remounting the manifold covers. Next, holes were dug in three layers in locations 2 - 7. Three photographs were taken in each location, one with about every 6 inches of depth. For example, after digging 6 inches into the ground, one picture was taken. After digging 12 inches into the ground, another picture was taken. The final picture for each location was taken after a depth of about 18 inches had been reached. All of the holes were dug out in areas of the wetland that were not directly covered by a growing plant. All of the holes were dug out one after the other without taking water samples immediately. Only after all the holes were dug (in all cells) were water samples taken - systematically, again, starting from the first hole dug and moving to the last. This was done in order to allow for particulate matter to settle in each hole so that water samples could be taken without solids clogging the equipment. Water samples were only taken from locations 1 - 5 from each cell with the exception of locations 4 and 5 of cell 'C' where a pump used to collect water samples stopped functioning.

Plants:

Plants were dug out in each cell in 4 to 5 locations, roughly evenly spaced out from influent to effluent regions. Different plant species were dug out to examine root structure and depth achieved. Pictures were taken of all the plant roots and all plants were then re-planted into their original locations.

RESULTS

Photographical Results:

The pictures taken showed trends throughout each cell. Pictures taken of the media in cells 'A' and 'B' showed that, in general, the media was rather clean throughout. Location 2 showed darker gravel, generally at a depth between 12 to 18 inches, with color ranging from a dark brown into a gray. Locations 3 and 4 contained media that were generally the same color through the 18 inches dug. The only discoloration showed a light gray or light brown color. Cell 'C' contained media that was very dark at location 2 at all depths, turning into a deep jet-black color after about 8 inches. Location 3 also showed some deep black media at maximum digging depth while location 4 showed only slightly darker media as the hole got deeper, never reaching the black color. The pictures taken of cell 'C' showed much darker media as a whole as compared to cells 'A' or 'B'. The media in cell 'B' was nearly the same as the media in cell 'A' but appeared to have some more gray shades in deeper depths.

The plants that were dug up in all cells had shallow roots that did not exceed a foot of depth at any location. Some of the tallest plants could not be easily dug up due to their massive and deep root systems. The plants that contained the deep root systems were identified as the *Carex* genus. In some cases, plant root systems were wider than they were deeper. These plants were identified as the *Scirpus* genus. Cells 'A' and 'B' showed the roots to be rather clean and healthy where plants were present. Plants nearer to the influent manifolds were showed only slightly darker roots (or darker particles on their roots). Plants in cell 'C' nearest the influent manifold had roots that were dark, similar to the gravel that was dug up. Plants that were dug up closer to the effluent manifold seemed healthier and had cleaner roots like the plants in cells 'A' and 'B'.

Water Testing Results:

The available water samples were tested for Ammonia concentrations. Cells 'A' and 'B' each had five sample points while cell 'C' had only three sample points, the ones nearest to the influent region. Figure A.6 shows the results of the ammonia tests done on each sample - both the numerical values can be seen along with a graphical trend. In general, data for cells 'A' and 'B' show highest ammonia concentration at the influent manifold and decreasing concentrations while moving toward the effluent manifold. Cell 'C' data shows fairly consistent ammonia concentration at the influent manifold and location 2 and also shows a much smaller decrease in concentration from locations 2 to 3 as compared to cells 'A' and 'B'.

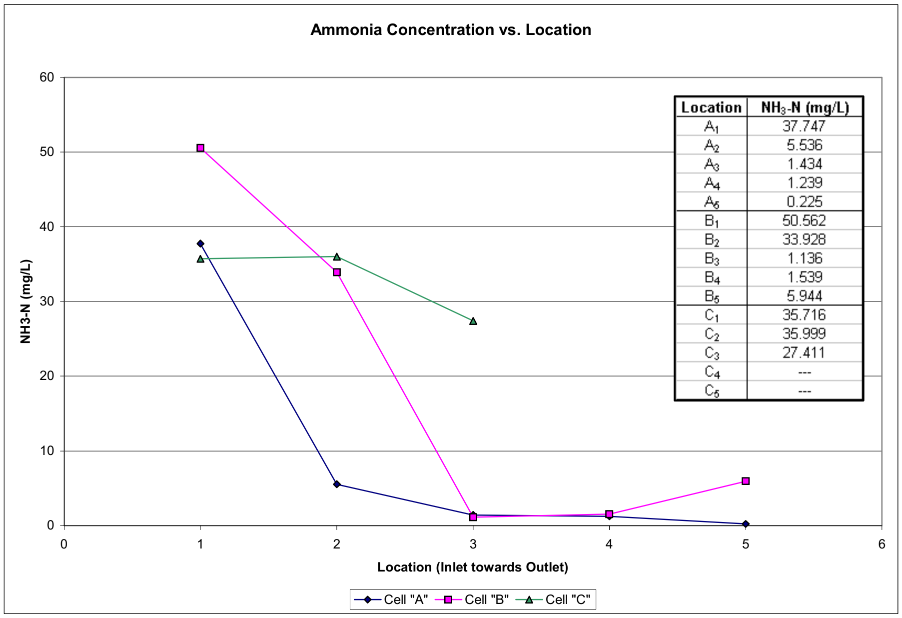

Figure A.6 - Ammonia concentrations vs. locations within cells A-C.

DATA ANALYSIS

Taking into account the visual observations of the media growth within each cell (Figs. A.2 & A.3), the photographs taken of the vegetation and media, and the results of the tests performed on the water samples, several conclusions can be reached regarding the wetland system at France Park.

The photographs taken of the plants as well as the observations seen in Fig. A.5 show many more plants growing in cell ‘C’ as compared to cells ‘A’ and ‘B’ as well as larger root systems for the plants in cells ‘B’ and ‘C’. There is a greater breadth of species in cell ‘C’ as well. There is much less dry area nearest the effluent region of cell ‘C’ as compared to cells ‘A’ and ‘B’. Pictures taken of the gravel show the media to be darker in cell ‘C’ than that of cells ‘A’ or ‘B’. This dark color of the gravel and roots shows that not as much oxygen as reached at those particular locations resulting in ferrous ions to accumulate, resulting in the dark colors. Furthermore, the pictures of the water near the valves at locations 1 and 5 of cell ‘C’ show water that is much dirtier (darker) when compared to same locations of cells ‘A’ or ‘B’. Cell ‘B’, however, has dirtier water at locations 1 and 5 as compared to cell ‘A’. The water at locations 1 and 2 of cell ‘C’ smelled considerably worse than the same locations of cells ‘A’ or ‘B’.

Taking into account all of these factors the conclusion can be made that cell ‘C’ receives more water than the other cells - or cell ‘C’ has a higher retention time than the others. Also, cell ‘B’ may have a slightly higher flow rate than cell ‘A’.

SUMMARY

In general, the wetlands at France Park appear to be doing well. Much of the original wetland vegetation that was installed has been replaced with invasive plant species or is missing as seen by the dry areas. However, the wetland plants that are present seem to be growing well. The plants appeared to have varying root systems. The plants with deeper and wider root systems were much more difficult to pull out of the wetland and were vary large. This leads to the conclusion that the larger the plant above ground, the greater the biomass below ground.

The testing done on the water samples shows that water that reaches the effluent manifold in cells ‘A’ and ‘B’ is very clean with very low ammonia concentrations. The removal percentages for cells ‘A’ and ‘B’ are 99.4% and 88.2% respectively. This may be due to a higher retention time within those wetland cells and can be credited to plant media growth.

Cell ‘C’ most likely has a higher flow rate than the other two cells. This may be the result of a problem with valve adjustment in the manifolds. This higher flow rate is responsible for the discoloration of the gravel and roots of the vegetation. The discoloration indicates a lack of oxygen presence in the root zone of this cell, thus allowing for less bacterial activity. Because of the increased flow rate, hydraulic retention time may also be shorter, a conjecture further supported by the worsened water quality data.

APPENDIX B. WETLAND PROJECT TIMELINE

Time	Items	Remarks
June, 2000	**Original JTRP proposals (Purdue)** The original research project was developed in a set of 3 proposals submitted to Joint Transportation Research Program (JTRP): • Constructed Wetlands for INDOT Rest Stop Wastewater Treatment: Proof-of-Concept Research Investigation • Constructed Wetland Systems for Wastewater Management • Hydrology of Natural and Constructed Wetlands **Biofield Cost Estimated** by JF New -- **$29,600**	
June, 2000	**Feasibility study (JF New)** Key points in the document: • Proposed a horizontal plug-flow constructed wetland pretreatment system • Average daily flow: 5,000 gpd; Peak daily flow: 15,000 gpd • 11,000 ft^2 surface area • Acknowledged poor nitrogen removal efficiency (17%) in winter months • Cost estimates: one 10,000 septic tank + 11,000 ft^2 wetland cell - $133,800 • Annual O/M cost: $1,200	Assuming a cell depth of 1.5 ft, HRT for the wetland is 3.4 days for peak flow and 7.4 days for average flow. Adding a 10,000-gal septic tank will increase the HRT by 0.7 day for peak flow and 2 days for average flow.
Aug, 2000	**Combined proposal (Purdue)** The 3 original proposals were consolidated into one master "INDOT Rest Stop Constructed Wetland Evaluation" project with 3 components: • Biofield Unit Placement • Hydraulic Aspects • Environmental Aspects	However, for accounting purposes the three projects were still kept separately.

Aug, 2000	**Evaluation of treatment options (Email from Mark L. Sneathen, RQAW, Aug. 14)**
	Presented 3 options:
	• Option 1: *Paying surcharge and installing ozonator*
	  o Cap. cost: $30,000
	  o Annual O/M: $3,000
	• Option 2A: *Wetland pretreatment with no biofield*
	  o Cap. cost: $222,000
	  o Annual O/M: $1,875
	• Option 2B: *Wetland with biofield*
	  o Cap. cost: $222,000 + $35,000
	  o Annual O/M: $510
	• Option 3: *Biomechanical pretreatment system*
	  o Cap. cost: > $270,000
	  o Annual O/M: $20,000
		For Option 2B, it was assumed that all the effluent was discharged to the biofield.

Oct, 2000	**SAC meeting (Oct. 23)**
	• Purdue would pay for construction of the biofield
	• Estimated construction time: Spring 2001
	• Barry Partridge would like to see the following items discussed in the final report:
	  o Cost comparisons
	  o Performance of wetland and biofield	

	○ Wetland vegetation ○ O/M of wetland system ○ Design guidelines	
Nov, 2000	**Batch system design (JF New)** JF New proposed a design with an alternating drain-and-fill cycle between the two parallel wetland cells.	
Feb, 2001	**SAC meeting (Feb. 27)** • Due to high ammonia loads, lime stone was suggested to mix in with the gravel for the wetland medium to increase buffer capacity (alkalinity). • Proposed instrumentation for the system was presented by Tom Cooper. • Effluent filters were suggested for the septic tank. • Tentative construction schedule was discussed. Construction permit had not been obtained. Expected completion date: July 4.	
Apr, 2001	**Construction cost estimate proposal (Apr. 26) (RQAW, Berns Construction Company, Heritage Industrial Servies)** Entire construction cost was estimated to be: $418,975	
May, 2001	**Retrospective cost analysis (RQAW, JF New, Purdue)** Comments from JF New: • Drew Bender ○ Public job more expensive ○ Higher ammonia loading ○ Larger biofield (poor soil loading rate) ○ "Bell and whistles" • Ted Blahnik ○ Design flow increase: 5,000 gpd → 10,000 gpd ○ Additional effluent piping ○ Recirculation system ○ Aeration chamber ○ Sampling and monitoring equipement Comments from RQAW (Mark Sneathen): • Essentially same design flow (smaller wetland surface area) • One extra septic tank • Force main from softener building Analysis by Purdue: • Reduced surface area but increase in depth (1.5 ft → 2.75 ft) • Change of system operating mode: from conventional plug-flow to batch cyclic drain-and-fill • Apparent increase in cost due to non-competitive bidding	
June, 2001	**Strategic plan (Purdue, Jun. 7)** A game plan was prepared to outline the steps leading to the construction of the wetland system.	
July, 2001	**Revised Design (Jul. 2, Purdue)** In an effort to reduce construction cost and streamline treatment design, Purdue proposed a revised wetland system with the following items: • Additional third wetland cell for effluent polishing	

	• A much smaller biofield • Recirculation to the second septic tank Purdue would pay for the re-design costs of the system.	
Oct, 2001	**SAC meeting (Oct. 11)** • Gary Duncan (RQAW) presented the revised wetland design.	
Oct, 2002	**SAC Meeting (Oct. 28)** • Phase I monies ($100,000) to be used by December, 2002. Request for Phase II monies ($80,000) to be made to the JTRP board in *November, 2002*. • Jim Alleman (Purdue) had a discussion with Ed Miller (ISDH) regarding a construction permit for the wetland system. This permit was still not attained.	Tentative meeting scheduled to resolve permitting issues, Nov. 6th.
Dec, 2002	**Construction Begins**	
June, 2003	**Site Visit & Meeting (Jun. 5)** • Vanderpool and Mason (INDOT) were very concerned with overflow to cells and mentioned alarms needed. • Neither septic tank had any level sensor or alarm • The access hatch for the flume box was not gasketed, likely odor. • The issue of shallow side walls and rough installation of wetland cells brought up the concern for membrane tears or punctures.	JF New was not concerned, claimed 3:1 slope was intended and appropriate.
Aug, 2003	**Wetland Cells Planted (Aug. 12)** • 3,820 plants, 13 different species.	

Oct, 2003	**SAC Meeting (Oct. 14)**
	• Implementation time of SCADA system is still unknown.
	• Clyde Mason (INDOT) suggested subsurface discharge
	• **Operation and Maintenance Manual** was discussed.
	    o Responsibilities of Purdue, RQAW and INDOT to be clearly spelled out.
	    o Tom Vanderpool (INDOT) suggested "decision tree" structure including emergency procedures and contacts.
	• High flow rates from south side ostensible on *October 11th* caused surges in the first septic tank, preventing settling and submerging the V-notch weir in between septic tank 1 and 2. Discussion of clogged filters and wetland media led to immediate actions.
	    o South side flow was shut down, leaving only north side flow into the wetland system.
	    o A meeting with RQAW was requested to determine pump operation data from the south side.
	• Installation of a surge tank upstream of septic tanks was discussed.
	• Posters of the site were presented. Purdue agreed to
		Tight clays make subsurface discharge very difficult.

	send electronic versions and hard copies to INDOT, Greenfield.	

Oct, 2003	**Pre-Startup Meeting (Oct. 27)**
	• The need for an **emergency generator** was discussed.
	  o Clyde Mason (INDOT) said power was lost to the site often.
	  o A high demand on the electric system could cause problems including heat buildup in system panels.
	• Flow sheets reviewed for *September, 2003* showed 9k-10k maximum per-day average for the system.
	• High pumping rate from south side. Discussed solutions included installing a smaller diameter force main, constructing a surge tank, or (ideally) putting a septic tank on the south side.
	• Flow from the pumps (LS1) should have been around 72 GPM, but were measured at 38 GPM - it was determined that some kind of restriction was the problem, possibly a check valve problem.
	• Heritage to sort out problems with pumps and outlets. Purdue to start looking at settleability from water samples. JF New to develop O & M draft. RQAW to develop surge tank design and cost estimate.
		Existing demand is 44.5 kW, 2/3 of service (66 kW). Proposed generator to use natural gas to drop demand.
		• 100 kW generator costs $20k-$24k
		• 200 amp breaker to reduce load by ½ costs $40k-$65k

Nov, 2003	**Pre-Startup Video Conference (Nov. 6)** • The 38 GPM pumping rate from LS1 was still a problem; a pipe was supposedly crushed. Brian Morgan was to fix the problem. • Postponement of surge tank design was decided until LS1 becomes fully functional so that the surging problem can be re-examined. • Discussion of the V-notch weir led to the conclusion that the septic tanks should be checked by a certified inspector. • The O & M manual was to be completed by JF New by Nov. 25th.	
Dec, 2003	**(Dec. 22)** Wastewater samples collected by Purdue for analysis.	
Dec, 2003	**30,000 GPD flow rate recorded (Dec. 29)** System was temporarily shut down. Westbound wastewater was now fed into the wetland system while eastbound wastewater was sent back to the city. Recirculation was terminated.	Normal flow rate should be 5,000 GPD.
Mar, 2004	**On-Site Meeting (Mar. 5)** • Gary Duncan (RQAW) pointed out insufficient gas line and suggested installation of new regulator, $25,000 cost. • Decision reached to proceed with surge tank design (RQAW, JF New) based on estimated 400 GPM flow from south side. • **SCADA system cost estimate** was to be determined by Gary Duncan. A meeting was suggested for further discussion. • Magmeter M2 was not working (bad coil on the	

	sensor) and was given to Tom Cooper for repair. • Installation of a concrete base for the weather station was to be provided by Bryan Morgan according to Tom Cooper's spec's.	

Mar, 2004	**SAC Meeting (Mar. 19)**
	• T. P. Chan (Purdue) provided an update of activities and problems that were encountered. Spikes in the flow data were discussed.
	• The septic tanks had been pumped and cleaned. Sludge was about 2 ft. from the top. Costs were \$530 per 400 gallons.
	• Surge tank design had started (Gary Duncan). Clyde Mason (INDOT) suggested that any flow over 10,000 GPD be diverted to the city without flow through wetlands.
	• Barry Partridge (INDOT) wanted to see the following in a report:
	  o Economics of having a wetland-biofield with and without access to city POTW.
	  o Impact of winter months.
	  o Site properties conducive for this technology.	

May, 2004	**SAC Meeting (May 25)**
	• Voltage surges resulted in complete system shutdown during the last week of March.
	• SCADA System - T. P. Chan (Purdue) suggested that a 3-way valve is installed to control drainage to maximize system HRT.
	• New generator designs will be sent to INDOT by RQAW.
	• Discussion of a tentative surge tank design included:
	  o A 5,000 gallon tank, at least 5' of free board.
	  o (2) 72 GPM grinder pumps (time controlled).
	  o Three floats - High, Low, Low-Low.
	  o Located next to North side lift station.
	  o Magmeter installed to monitor total feeding flow.
	• Cell 3 plants were not doing well. Dave (JF New) said there is a maintenance issue resulting in no warranty.
	• Many invasive plants were found in the cells and wetland plant roots did not extend past the peat layer. Dave (JF New) suggested that water levels be lowered, said there was lack of nutrients.
	• High groundwater table caused water pockets to form under cell liners. Flow data could have been affected by leaks in the system.
	• F-3 Ultrasound sensor was damaged due to high water levels.
	• Brian Morgan (Heritage) fixed the check valve problem; LS-4 functions at full capacity now.
	• Gary Duncan resigned, **Matt Moore** new RQAW
		Elec. Company lowered voltage to "fix" problem. Voltage problems caused flooding.
		
		If 30% or more plants die within 1 yr. of planting, more would be considered.

	project manager.	
June, 2004	**Purdue University (Jun. 7)** A new data logger was installed by Tom Cooper in order to store more data. Data will not need to be collected as often.	Tank is only **4,000** gallons.
June, 2004	**SAC Meeting (Jun. 15)** • A gas generator will be set up with a 200 amp capacity. • David Latka (JF New) presented the final design of the surge tank. • Greg Pankow (INDOT) stated that INDOT wants to wrap up their contractual bindings. • An agreement was reached to follow through with the surge tank. JF New was to deliver plans to RQAW by the end of June, RQAW to deliver to Heritage by 1st week of July, Heritage will send price to INDOT by the 2nd week of July. • SCADA plans were ready and were to be delivered by John Downs (Integrity) will deliver them to Heritage through RQAW.	
Sept, 2004	**SAC Meeting (Sept. 23)** • Performance of the wetland was noted to be less than desired. • Monies allocated in 2000 are still being used by Purdue, and would likely last another year before additional funds would be requested. • A new cost estimate for the surge tank was less than originally anticipated (note that the size has changed to 4,000 gallon cap.). • INDOT (Greg Pankow and others) expressed their desire to have all construction at the site be completed by the end of this calendar year (December 2004). • The issue of weeds was brought up by Jim Alleman. Jim said that he would contact JF New regarding maintenance of the wetland.	
June, 2005	**System instrumentation damaged, presumably by lightening** • Five pieces of equipment were damaged. Tom Cooper sent these instruments back to dealers for repair.	Unable to monitor flow at all stations due to broken equipment.
June, 2005	**Surge Tank Installation Began** • 4,000 gallon surge tank • North side of the rest area (west bound lanes) installed near the restroom building.	
Aug, 2005	**SAC Meeting (Aug. 26)** • Invasive species were becoming a problem. Responsibility of removal was uncertain and expertise was limited. Clyde Mason said that he would find out if one of the herbicide coordinators could be trained to take care of this. • A power surge (presumably from a lightening strike) damaged some instrumentation in June of 2005. o 5 instruments had been damaged and sent	Purdue created electronic file of wetland plant information for original species planted.

	back to dealers for repair. o The instruments have since arrived and will be reinstalled. • Tom Duncan said he would find out more about the status of the SCADA system over the next week. • INDOT (Greg Pankow) expressed concern that there had been no representative from FHWA in the past several meetings. • Effluent quality was reported by Purdue: o High percentage removal in wetland cells. o Surface discharge standards are not yet met, but the water may qualify for discharge to the city without surcharges. • Biofield sampling is to be conducted in the future. • INDOT (Greg Pankow) stated that the project needs to be closed soon. SCADA and generator still have not been paid for. • Steve Land informed the group that there was a possibility of the first septic tank might have developed a crack; it may need repair.	
Aug, 2005	**Surge Tank Installation Completed**	
Feb, 2006	**SAC Meeting (Feb. 24)** • The current state of the wetland was discussed. o The wetland plant species in all cells were affected by the surge tank installation where flow was restricted to the wetland system. o Many plant species are no longer present, and the remaining plants appear to be dying. o A vast amount of invasive species (weeds) are present in the cells. • JF New will decide whether or not to replant the wetland cells based on the wetland species' ability to re-grow.	
May, 2006	**Wetland Cells replanted** • Clyde Mason replanted all of the wetland cells with a number of plants. After observation it was noted that not all original plant species were replanted, only a select few.	
June, 2006	**SAC Meeting (Jun. 7)** • Water effluent quality was discussed. • **A downward trend was noted in effluent quality**. TSS, NH3, and BOD removal have been decreased, possibly due to inconsistent flow to the wetlands, which may have caused the plants to die and decrease in quantity, thus causing the decreased removal. o A possible need to replant the wetland cells may be justified. • Water flow data was discussed. o There are gaps in the flow data. • Equipment failure after the presumed lightening strike. • The data logger was unplugged	

	during surge tank construction and SCADA system installation. • There are inherent measurement problems with the instruments. o Rebeka Sultana has developed a **hydraulic model** of the wetland system. • The SCADA system was discussed. o Data since January 2006 was in question as to who had it and how it could be accessed. o A training schedule for the SCADA system is needed. o Web access of the system and/or data - is this possible? • Recycle pumps are not working as of May 22, 2006. • Data from the biofield was discussed. o Samples are only available from the deepest well. o Samples show that treatment is not as desired and flow to the biofield should be shut off. • Data availability was discussed. Should raw data be put on a website or is data presented at meetings enough detail?	
April, 2007	**SAC Meeting (Apr. 24)** • Problems with the SCADA system were identified and discussed. o Clyde Mason mentioned that flow rates outputted by the system were high; beyond 5000 gpd as expected. o SCADA data was not available through the system's website for a number of weeks. o Joan Wooldridge stated that controlling flow rates into the wetland system from the surge tank is difficult. o Clyde Mason stated that Integrity Systems had asked for more funds to fix the SCADA system. • New shredder pumps were installed in the surge tank in late January, 2007. • Wetland cost information was requested of INDOT by Purdue University in order to perform a cost study of the Greenfield wetland. • INDOT determined that the septic tanks need to be emptied at least once a month to prevent clogging. • Clyde Mason informed of the use of high pressure emitters to release the wetland effluent into the landscape in a controlled manner.	
Jan., 2008	**SAC Meeting (Jan. 24)** • The waste stream from the north side was being pumped to the city, while the south side was being directed to the wetland. The septic tanks were needed to be cleaned almost once every month. • The concluded-exit strategies were discussed	

	• The contents of final reports are discussed.
	  ○ Joan said she would provide information on annual pumping costs, maintenance costs, and surcharge rates.
	  ○ Barry wanted to have some discussion on pros and cons of wetlands in the final report.
	  ○ Given the interim reports, the final report was expected to be brief. It would discuss basic design, talk about capital costs, operation and maintenance costs, and do a comparison with existing packaged treatment plants (if data became available).
	  ○ It was suggested to compare the performance of this wetland with some other existing studies.	

April, 2008	**Closure Meeting (Apr. 8)** • Schedule for the removal of monitoring equipments	
May, 2008	**Removal of Automatic Samplers (May 29)**	